A Comparative Limnological Survey of 19 Sockeye Salmon *(Oncorhynchus nerka)* Nursery Lakes in the Fraser River System, British Columbia

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A COMPARATIVE LIMNOLOGICAL SURVEY OF 19 SOCKEYE SALMON (*Oncorhynchus nerka*) NURSERY LAKES IN THE FRASER RIVER SYSTEM, BRITISH COLUMBIA

by

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ABSTRACT

Stockner, J.G., and K.S. Shortreed. 1983. A comparative limnological survey of 19 sockeye salmon (Oncorhynchus nerka) nursery lakes in the Fraser River system, British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 1190: iv + 63 p.

Results of a fall limnological survey of 19 lakes in the Fraser River system are presented. Lakes were grouped into broad biogeoclimatic zones and zonal averages of selected limnological variables were used as "production indices" to facilitate comparisons among zones, and with other B.C. coastal and Yukon River Basin lakes. The most productive lakes of the Fraser system were in the Interior Plateau Zone (Zone A), followed by lakes in the Columbia Mountain Zone (Zone B), which in turn were more productive than lakes of the Coast and Insular Mountain Zone (Zone C). Values of "production indices" for Fraser Zone C lakes were very similar to average index values from coastal lakes situated along the entire 1200 km coastline of B.C., suggesting a common influence of climatic and edaphic factors throughout this extensive zone. A South to North trend toward increasing lake "productivity indices" values was apparent when "interior" Fraser lakes (Zones A and B) were compared with interior Yukon River Basin lakes. We consider this marked latitudinal trend to be related to regional differences in climatic and edaphic factors which influence supply, retention and concentration of nutrients in lakes. Several Fraser River lakes were identified and ranked as potential candidates for lake fertilization to enhance sockeye salmon production.

Key words: limnology, fisheries, lake fertilization, nutrients, bacteria, phytoplankton, zooplankton, sockeye salmon.

RÉSUMÉ

Stockner, J. G., and K. S. Shortreed. 1983. A comparative limnological survey of 19 sockeye salmon (Oncorhynchus nerka) nursery lakes in the Fraser River System, British Columbia. Can. Tech. Fish. Aquat. Sci. 1190: iv + 63 p.

Les auteurs présentent les résultats d'une étude limnologique, faite à l'automne, de 19 lacs du système hydrographique du fleuve Fraser. Pour faciliter les comparaisons entre les différentes zones et avec d'autres lacs côtiers de la Colombie-Britannique et du bassin du fleuve Yukon, ils ont réparti les lacs en grandes zones biogéoclimatiques et utilisé comme "indices de productivité" des moyennes zonales de variables limnologiques sélectionnées. Les lacs les plus productifs du réseau du Fraser ont été trouvés dans la zone du plateau intérieur (zone A); ils sont suivis par les lacs de la chaîne Columbia (zone B), eux-mêmes plus productifs que les lacs côtiers et insulaires de la zone montagneuse (zone C). Les valeurs des "indices de productivité" des lacs de la zone C étaient très proches des moyennes de celles des lacs côtiers situés sur les 1 200 km de coté de la Colombie-Britannique, ce qui laisse supposer l'existence d'une influence commune de facteurs climatiques et édaphiques dans cette vaste zone. La comparaison entre les lacs intérieurs du système hydrographique du Fraser (zone A et B) et ceux du bassin du fleuve Yukon a montré que les valeurs des "indices de productivité" augmentaient lorsqu'on remontait du sud vers le nord. Les auteurs pensent que cette tendance latitudinale marquée se rattachent aux différences régionales des facteurs climatiques et édaphiques, qui ont une influence sur l'apport, la rétention et la concentration de matières nutritives dans les lacs. Ils ont classé plusieurs lacs du fraser quant à leur potentiel de fertilisation pour une production accrue de saumon rouge.

Mots-clés: limnologie, pêche, fertilisation de lacs, matières nutritives, bactérie, phytoplancton, zooplancton, saumon rouge.

INTRODUCTION

There is a paucity of published information on the limnology of Fraser River lakes. Early work focused on estimates of zooplankton abundance in Fraser lakes as a means of determining the potential food supply for rearing juvenile sockeye salmon (Foerster 1925, Ricker 1934, 1937 a,b, Ward 1957, Geen and Andrew 1961, Goodlad et al. 1974). The only limnological studies that considered the importance of lake physics and chemistry on biological production were the studies of Ricker (1937a, 1938), Northcote and Larkin (1956), Ward (1964), and St. John et al. (1976).

The primary objective of this synoptic survey was to collect preliminary limnological information on the relative productivities of selected sockeye nursery lakes in the Fraser River system, and to compare and contrast these observations with similar data from the coastal lakes of British Columbia and interior lakes of the Yukon River Basin. Enrichment of sockeye nursery lakes with nitrogen and phosphorus fertilizers is an established sockeye enhancement technique in coastal British Columbia lakes (Stockner 1979), and in future may be applied to lakes of the Fraser River system. Data collected in this study will be invaluable when selecting potential candidate lakes for further study and subsequent fertilization. The study was initiated by the Department of Fisheries and Oceans, Salmonid Enhancement Program (SEP), and was conducted by personnel associated with the Lake Enrichment Program.

DESCRIPTION OF STUDY AREA

The 19 lakes sampled in this study were located within three broad biogeoclimatic zones (Fig. 1). Mean annual precipitation (29 year averages) varies among zones, ranging from 30-35 cm in Zone A and 65-75 cm in Zone B to 160-170 cm in Zone C (Atmospheric Environment Service 1971). Zone C lakes can be further subdivided on the basis of annual precipitation into high rainfall Coastal Mountain lakes (Harrison, Pitt) receiving 170-200 cm, and Insular Mountain lakes (Anderson, Chilko, Lillooet, Seton, Taseko) receiving 62-95 cm. The lakes ranged in latitude from 49°N to 55°N and in elevation from <10 m to 1321 m (Table 1). All lakes with the exception of Pitt (sampled in January) and portions of Chilko, Fraser and Lillooet lakes were thermally stratified at the time of sampling. Four lakes are warm monomictic (Harrison, Lillooet, Little Shuswap and Pitt) and the remainder are dimictic (T. Gjernes, pers. comm.). Five lakes (Chilko, Harrison, Lillooet, Seton and Taseko) had varying degrees of glacial turbidity at the time of sampling and the remainder were clear or slightly humic-stained.

METHODS

Sampling stations were located in the main basins of the 19 Fraser lakes (Fig. 2-14). The 59 stations were sampled once only, in September or early October, 1981, using a float-equipped de Havilland Beaver aircraft. Pitt Lake was sampled in January, 1982. Data from the B.C. coastal and Yukon Basin lakes used for comparative purposes were obtained in September, 1982.

Temperature profiles to a maximum depth of 50 m were obtained at most stations using a Montedoro-Whitney temperature probe (Model TC-5C). Buoyancy frequencies (Turner 1973) were calculated and used to determine epilimnion depth. Water column stability to a depth of 50 m was calculated using a modified Schmidt stability function (Costella et al. 1983).

A Li-Cor light meter (Model 185A) equipped with a quantum sensor (Model 192S) was used to measure photosynthetically active radiation (400-700 nm) from the surface to the compensation depth (1% of surface intensity) and vertical light extinction coefficients were calculated. A standard 22-cm white Secchi disc was used to measure water transparency.

A 3-L Van Dorn bottle, rinsed with 95% ethanol, was used to collect all water samples. Samples were usually collected between 0900 and 1200 h. Generally, two epilimnetic and two hypolimnetic depths were sampled for nutrient analysis (ammonia, nitrate, total phosphorus, total dissolved phosphorus, and soluble reactive silicon). Three epilimnetic and one hypolimnetic depths were sampled for bacteria numbers, chlorophyll and phytoplankton identification and enumeration.

An unfiltered sample was placed into a clean, rinsed test tube, stored in the dark at 4°C, and analyzed later for total phosphorus. Samples for the remaining nutrients and chlorophyll were stored for 2 to 4 h in 1-L polyethylene bottles and kept cold and in the dark. At the field laboratory 55-mm Whatman GFF filters, which had been previously ashed and washed with 500 mL distilled water, were used to filter the nutrient samples. The filter was placed in a 47-mm Swinnex (Millipore Corp.) filtering unit. An additional 500 mL of distilled water were passed through the filter, followed by 50-mL aliquots from each depth. One filter was used to filter all samples from each station unless high algal biomass inhibited filtering efficiency. A glass bottle was rinsed then filled with 100 mL filtered sample, covered with ashed and washed aluminium foil and capped tightly. This sample was analyzed later for nitrate concentration. Approximately 100 mL of sample was filtered into a rinsed, plastic bottle and analyzed later for soluble reactive silicon, ammonia and total dissolved solids. A 25-mL test tube was rinsed and filled with filtered sample and analyzed later for total dissolved phosphorus concentration. All samples were stored cold and in the dark.

A 500-mL sample was filtered under subdued light through a 47-mm diameter, 0.8 µm Millipore filter and a few drops of a $MgCO_3$ suspension were added. Filters were folded in half, dried in a dessicator overnight, then stored frozen and analyzed later for chlorophyll using a Turner fluorometer (Model 111). All analyses were done according to the methods of Stephens and

Brandstaetter (1983).

A glass jar was filled completely with water from one of the epilimnetic depths, covered with parafilm and transported to the field laboratory. Total alkalinity and pH were determined (APHA 1976), and dissolved inorganic carbon (DIC) estimated from pH, temperature, total dissolved solids and alkalinity. Additional samples for DIC analysis were collected from Francois, Fraser, Pitt, Stuart, Takla and Trembleur lakes and analyzed with a Carle gas chromatograph (Model 211 M) using the method of Stainton et al. (1977). Samples were collected in 50-cc plastic syringes and 1 mL of 2 N H_2SO_4 was added in the field; then the samples were transported to the field laboratory. Standards were prepared daily from a factory standard (1000 mg $C \cdot L^{-1}$) and distilled, deionized water. Duplicates of each standard (10, 5, 2, 1 mg $C \cdot L^{-1}$ and blank) were made and 1 mL of 2 N H_2SO_4 was added. To each standard and sample 30 mL of Helium gas (zero grade) were added and the sample agitated for approximately 15 s. Syringes were placed in an ice bath for a minimum of 10 min prior to injection into the gas chromatograph.

A test tube rinsed with 95% ethanol was rinsed and filled with sample water for bacteria enumeration. In the field laboratory 5 mL were filtered onto a 25-mm diameter, 0.2 µm Nuclepore membrane filter counter-stained with Irgalan Black. Filters were removed when just dry and placed in a 9-cm divided petrie dish lined with Whatman filter paper, air-dried at room temperature (approximately 20°C) and stored. Samples were counted later under epifluorescence using the acridine orange direct count (AODC) method as described by MacIsaac et al. (1981).

Samples for ultraphytoplankton (<3 µm equivalent spherical diameter) biomass were collected in opaque, 125-mL polyethylene bottles and transported to the field laboratory where 15 mL of each sample were filtered under subdued light onto a stained (Irgalan Black), 25-mm diameter, 0.2-µm Nuclepore membrane filter in the same manner as for bacteria biomass. Filters were then air-dried and stored in opaque, 9-cm petrie dishes until counts were made at 1250X magnification using a Zeiss compound microscope (Model KLSM) equipped with epifluorescence as described for bacteria biomass. Approximately 20 to 30 random fields were counted and values were converted to numbers $\cdot m^{-3}$ and volume ($mm^3 \cdot m^{-3}$). The remainder of the water in the opaque bottle was fixed with Lugol's acid solution and used to count phytoplankton >3 µm in diameter. Samples were shaken and allowed to settle overnight in 27-mL settling chambers. One transect at 187.5X and one at 750X magnification were counted using a Wild Heerbrugg M40 inverted microscope equipped with phase contrast microscopy (Utermöhl 1958). Counts were converted to numbers $\cdot m^{-3}$ and volume ($mm^3 \cdot m^{-3}$).

Zooplankton were collected using a 100-µm mesh size SCOR-UNESCO net (mouth area = 0.25 m^2). Vertical hauls at a speed of 0.5 $m \cdot s^{-1}$, were made at every station from 25 m to the surface with the following exceptions: Bowron-1, 20 m; Fraser-1, 20 m; Fraser-2, 10 m; Little Shuswap-1, 15 m; and Stuart-3, 45 m. All samples were preserved in a borax-buffered, 4% formalin-sucrose solution (Haney and Hall 1973). In the laboratory each sample was split in half using a Folsom plankton splitter. One portion was filtered onto a pre-weighed Whatman GFC filter, dried to a constant weight at 90°C for 24 h and weighed.

RESULTS AND DISCUSSION

FRASER LAKES: COMPARISON AMONG ZONES AND WITH BRITISH COLUMBIA COASTAL AND YUKON TERRITORY LAKES

Comparison of limnological results among Fraser River lakes was facilitated by dividing the lakes into three broad biogeoclimatic zones using boundaries proposed for British Columbia by Brink and Farstad (1949) (Fig. 1). Of the 19 lakes sampled, 5 were in Zone A (Northern Interior Plateau), and 7 lakes each were in Zone B (Columbia Mountains) and Zone C (Coast and Insular Mountains). Zone C was further subdivided into Coastal Mountain (2 lakes) and Insular Mountain (5 lakes). Lake and zonal averages of five chemical and biological variables that are useful lake productivity indices are summarized in Table 2. Zone averages for each of these variables are used as relative indicators of lake productivity, and will in the subsequent discussion be referred to as "production indices". Summarized results of all limnological variables measured are presented in Appendix Tables 1-6.

Among Zone A lakes, Fraser and Stuart lakes had the greatest phytoplankton biomass and Francois Lake the greatest zooplankton biomass (Table 2). Takla and Trembleur lakes had the lowest bacterial and algal standing stocks.

Lakes of Zone B were all very similar with Little Shuswap Lake having the highest standing stock of phytoplankton and Shuswap Lake the greatest zooplankton biomass and bacteria numbers. Quesnel and Adams lakes had the lowest standing stocks of phytoplankton and bacteria and Momich Lake had the lowest zooplankton biomass of lakes in Zone B.

Lillooet and Taseko lakes in Zone C (Insular Mountain) were heavily affected by glacial turbidity and had relatively low stocks of zooplankton, phytoplankton and bacteria. Their high turbidity affected phosphorus determinations and gave erronously high values, so these lakes and also moderately glacial Seton Lake were not included in Zone C (Insular Mountain) averages for total phosphorus. Seton Lake, though glacially influenced, had the highest chlorophyll content and Anderson Lake had the greatest zooplankton biomass in Zone C. Chilko Lake had the lowest stocks of bacteria and zooplankton of Zone C (Insular Mountain) lakes. Harrison Lake in Zone C (Coast Mountain) had low algal and zooplankton standing stocks. Pitt Lake was sampled in January, 1982, so the values presented are excluded from this comparison and from Zone C averages (Table 2).

For further comparison with Fraser lakes we have summarized limnological variables from a 1982 September survey of untreated coastal lakes which include lakes on the Queen Charlotte Islands, the mainland north coast and the west coast of Vancouver Island (Costella et al. 1983) under study by the Lake Enrichment Program (Table 2). The similarity between these coastal lakes and Zone C Fraser lakes is readily apparent and suggests a basic uniformity in lake production indices among lakes of the Coast and Insular Mountain zone that includes the entire 1200 km coast of British Columbia. By contrast, there was a notable difference in average values of the production indices between

Zones A and B "interior" Fraser lakes and Zone C Coastal and Insular Mountain Fraser lakes (Table 2), and though differences between Zones A and B were not as large as between Zone A and Zone C, there was an apparent trend toward higher productivity in the lakes of Zone A when compared to the more southerly Zone B lakes. When this comparison among Fraser "interior" lakes is extended further north to include Yukon River lakes sampled in September, 1982 (Stockner and Shortreed, unpubl. data), the latitudinal trend toward increasing lake productivity is even more apparent (Table 2). Average September values for the same five variables in Yukon River lakes (62°N), were generally higher than the Fraser River lakes of the Northern Plateau (Zone A) (55°N), which were in turn higher than Fraser River lakes situated in the Columbia Mountain zone (Zone B) (51°N). The resulting gradient in average Yukon and Fraser River "interior" lake production indices is not surprising in that climatic and edaphic features which control the supply and relative retention times of essential nutrients differ over this large geographic region (Farley 1979). Similarly, the uniformly low production seen among lakes of the large Coast and Insular Mountain zone illustrates, we believe, the overriding importance of climatic (rainfall) and edaphic (shallow, poorly-developed soils) influences on biological production of British Columbia lakes. Seasonal variation of total precipitation and its effect on water residence time and associated circulation patterns is the key climatic variable affecting lake productivity. It is the interaction of this variable with drainage basin soils (as determined by drainage basin geomorphology), that controls the supply, retention and associated concentrations of essential nutrients and other conservative dissolved elements in lake lacking significant anthropogenic inputs (Vollenweider 1968).

Northcote and Larkin (1956) considered length of growing season to be one of the most important factors influencing productivity of B.C. lakes, but incorrectly assumed that the length of the ice-free period corresponded to the length of the growing season. The majority of coastal lakes in British Columbia are warm monomictic (ice-free), which suggests a longer growing season; however, Stockner and Shortreed (1979), Stockner et al. (1980) and Shortreed and Stockner (1981) have shown that by late October autotrophic production is reduced to negligible levels and does not begin again until the onset of stratification, which usually occurs between mid-March and mid-April, depending on latitude and local climatic conditions. Furthermore, owing to the common occurrence of early spring phytoplankton production occurring beneath ice-cover (La Perriere et al. 1975, La Perriere 1981, Stockner and Shortreed 1978), the length of the growing season in dimictic lakes is often much longer than the ice-free season would suggest. While length of growing season does significantly influence annual productivity, there is considerably less difference in growing season length among dimictic Yukon and Fraser lakes and monomictic B.C. coastal lakes than was previously thought.

Though a single synoptic September comparison tells us little about annual productivities, the use of several variables to assess "relative" production indices provides a better means of lake comparison than a single variable alone (Northcote and Larkin 1956, Rawson 1960). Furthermore, to facilitate comparisons in synoptic survey work of this type it is important to obtain samples at a similar time period in the lake's production cycle (eg. spring or fall), and to choose only those variables which provide useful

information for comparison of relative productivity among lakes (eg. total phosphorus, bacteria. phytoplankton (chlorophyll) and zooplankton).

COMPARISON OF FRASER LAKES WITH FERTILIZED COASTAL LAKES

Several coastal sockeye nursery lakes have recently been studied as part of the Lake Enrichment Program (Stockner and Shortreed 1978, Stockner et al. 1980, Shortreed and Stockner 1981, Stockner 1981). Twelve of these lakes have been fertilized with nitrogen and phosphorus during the growing season to increase plankton production in anticipation of increasing the in-lake growth and/or survival of juvenile sockeye salmon. At the primary trophic level, annual rates of carbon production in fertilized coastal lakes have been similar to, and in some lakes may have exceeded, annual values for interior lakes (Stockner and Shortreed 1975, Stockner et al. 1980). This increased autotrophic response can also be seen when histograms of chlorophyll in September from Fraser lakes are compared with September chlorophyll values from three untreated and three treated coastal lakes (Fig. 15). Though a single survey of Fraser lakes does not enable us to evaluate seasonal qualitative differences (species composition, size-frequency distribution) between phytoplankton communities, our preliminary comparison for September suggests very similar phytoplankton communities between treated coastal and interior Fraser lakes.

Zooplankton communities in fertilized coastal lakes have not responded in a similar manner. Though zooplankton stocks have increased under treated conditions (Rankin et al. 1979), their biomass has remained below that seen in Zone A and B lakes (Fig. 16). When zooplankton size-frequency plots for interior and coastal lakes are compared with treated coastal (Fig. 17), it is apparent that densities in both treated and untreated coastal lakes are less than those in Zones A and B. In addition, there are far fewer large zooplankton (>1 mm) in Zone C lakes. These differences were seen even though the range of fish densities in coastal and Fraser lakes were similar (Goodlad et al. 1974, T. Gjernes, pers. comm.). Bosmina sp. was far more common in coastal lakes than in the interior, and Daphnia spp. was common in interior lakes but was infrequently found in coastal lakes. Cyclops sp. and Diaptomous sp. were common in all lakes (P. Rankin, unpubl. data). It appears that some factor other than phytoplankton food quality prevents zooplankton populations in coastal lakes from attaining the size distribution and/or biomass of those found in interior lakes. Neill (1978) attributed the absence of Daphnia pulex from several coastal lakes to a number of interactive factors, the more notable being food limitation, water quality (eg. pH), and Chaoborus predation. Further studies will be required to answer these questions.

A positive autotrophic and zooplankton response to fertilization can with some certainty be predicted to occur in any lake showing periods of nutrient deficiency, including large interior dimictic lakes. The magnitude of the response to fertilization in Zones A and B Fraser lakes cannot at present be predicted, given the inherent differences in the biotic communities of coastal and interior lakes.

CANDIDATE LAKES FOR FERTILIZATION

Although much can be learned about relative lake productivities from a single sampling date, much more intensive work is required before it is possible to select lakes to be fertilized (Stockner 1979). However, studies such as the present survey are useful in determining which lakes are suitable for intensive pre-fertilization investigations, and also enable some predictions to be made on the relative potential of the lakes' biota to respond favorably to nitrogen and phosphorus fertilization. In order to calculate fertilizer loading rates, nutrient composition, and frequency and duration of applications for each lake, seasonal variation of nutrient concentrations, of epilimnion depth, stability, and flushing rate, of water clarity, and of phytoplankton and zooplankton biomass, species composition, and production must be determined. These data are also essential in predicting and subsequently measuring the effects of nutrient additions on lake biota, and in determining and improving the efficiency of energy transfer among trophic levels.

The suitability of the Fraser River lakes within each biogeoclimatic zone for intensive pre-fertilization studies are ranked in Table 1. Ranks were assigned subjectively, but only after study of all variables measured in this study. Variables most important in the ranking procedure were compensation depth, total phosphorus, chlorophyll, algal species composition, bacterial numbers, and zooplankton biomass.

Zone A lakes

Takla Lake was ranked highest of all Zone A lakes, and was followed by the other lakes (Trembleur and Stuart) of the Stuart River system. On the basis of total phosphorus concentration, Fraser Lake was mesotrophic, and fertilization with nitrogen and phosphorus may produce deleterious algal blooms. However, additions of nitrogen alone may be of benefit, since this would most likely reduce the numbers of large undesirable cyanophytes, which currently occur in the lake for part of the growing season, to smaller phytoplankton (<30 µm in diameter) which are more suitable as a food source for zooplankton (Gliwicz 1975).

Zone B lakes

Quesnel Lake had the highest ranking of lakes in Zone B, and appeared to be one of the most oligotrophic lakes in the entire study. Adams Lake also appeared to be an excellent candidate for further study. Bowron and Shuswap lakes appeared to be more productive than either Quesnel or Adams lakes, but fertilizer additions to either lake would most likely stimulate production. The remaining lakes of Zone B (Momich, Mara and Little Shuswap) appeared to be relatively unproductive, but their very low water residence times (0.03-0.2 y) indicate that fertilizer additions would be relatively ineffective at simulating production.

Zone C lakes

Lake in Zone C were generally less productive than those in Zones A or B, and this trend was reflected to some extent in average sockeye smolt size

at migration (Goodlad et al. 1974). Chilko Lake produces some of the smallest sockeye smolts of any lake in the Fraser River system (Goodlad et al. 1974), and data from this survey indicate that it is one of the most oligotrophic Fraser River lakes. Accordingly, Chilko Lake was given the highest ranking of the Zone C lakes, and was followed by Anderson, Pitt and Harrison lakes. Both Pitt and Harrison lakes have a relatively constant fry recruitment from artificial channels and/or improved spawning facilities (Vernon MS 1982), and would be less susceptible to the difficulties encountered when fertilizing a lake with a variable (and unpredictable) fry recruitment (Stockner 1979). Lillooet and Taseko lakes were glacially turbid, with compensation depths of ≤2 m, and it is unlikely under these conditions that nutrients are the primary factor limiting production. Seton Lake was also glacially turbid, but to a lesser extent, and factors limiting its productivity can only be determined by further study.

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REFERENCES

American Public Health Association, American Water Works Association, and Water Pollution Control Federation. 1976. Standard methods for the examination of water and wastewater. 14th edition. Washington, D.C. 1193 p.

Atmospheric Environment Service. 1971. Climate of British Columbia, climatic normals 1941-1970. Can. Dept. Environ. 90 p.

Brink, V.C., and L. Farstad. 1949. The physiography of the agricultural areas of British Columbia. Sci. Agr. 29: 273-301.

Costella, A.C., B. Nidle, and K.S. Shortreed. 1983. Limnological results from the 1981 British Columbia Lake Enrichment Program. Can. MS Rep. Fish. Aquat. Sci. 1693: 277 p.

Farley, A.L. 1979. Atlas of British Columbia. The Univ. of Brit. Columbia Press, Vancouver, B.C. 136 p.

Foerster, R.E. 1925. Studies in the ecology of the sockeye salmon (Oncorhynchus nerka). Contrib. Can. Biol. 2(16): 335-422.

Geen, G.H., and F.J. Andrew. 1961. Limnological changes in Seton Lake resulting from hydroelectric diversions. I.P.S.F.C. Prog. Rep. No. 8, 76 p.

Gliwicz, Z.M. 1975. Effect of zooplankton grazing on photosynthetic activity and composition of phytoplankton. Verh. Internat. Verein. Limnol. 19: 1490-1497.

Goodlad, J.C., T.W. Gjernes, and E.L. Brannon. 1974. Factors affecting sockeye salmon (Oncorhynchus nerka) growth in four lakes of the Fraser River system. J. Fish. Res. Board Can. 31: 871-892.

Haney, J.F., and D.J. Hall. 1973. Sugar-coated Daphnia: A preservation technique for Cladocera. Limnol. Oceanogr. 18(2): 331-333.

La Perriere, J.D. 1981. Vernal overturn and stratification of a deep lake in the high subarctic underice. Verh. Internat. Verein. Limnol. 21: 288-292.

La Perriere, J.D., L.A. Casper, and F.C. Payne. 1975. Difficulties in assigning a trophic state to a deep subarctic lake. Verh. Internat. Verein. Limnol. 19: 480-486.

MacIsaac, E.A., K.S. Shortreed, and J.G. Stockner. 1981. Seasonal distributions of bacterioplankton numbers and activities in eight fertilized or untreated oligotrophic British Columbia lakes. Can. Tech. Rep. Fish. Aquat. Sci. 994: 43 p.

Neill, W.E. 1978. Experimental studies of factors limiting colonization by Daphnia pulex Leydig of coastal montane lakes of British Columbia. Can. J. Zool. 56: 2498-2507.

Northcote, T.G., and P.A. Larkin. 1956. Indices of productivity in British Columbia lakes. J. Fish. Res. Board Can. 13(4): 515-540.

Rankin, D.P., H.J. Ashton, and O.D. Kennedy. 1979. Crustacean zooplankton abundance and species composition in six experimentally fertilized British Columbia lakes. Fish. and Mar. Serv. Tech. Rep. 897: 27 p.

Rawson, D.S. 1960. A limnological comparison of twelve large lakes in northern Saskatchewan. Limnol. Oceanogr. 5(2): 195-211.

Ricker, W.E. 1934. Plankton organisms and their relation to the sockeye of Cultus Lake. Biol. Bd. Canada, Pac. Prog. Rep. No. 21: 14-17.

Ricker, W.E. 1937a. Physical and chemical characteristics of Cultus Lake, British Columbia. J. Biol. Bd. Canada. 3(4): 363-402.

Ricker, W.E. 1937b. The food and food supply of sockeye salmon (Oncorhynchus nerka Walbaum) in Cultus Lake, British Columbia. J. Biol. Bd. Canada. 3(5): 450-468.

Ricker, W.E. 1938. Seasonal and annual variations in quantity of pelagic net plankton, Cultus Lake, British Columbia. J. Biol. Bd. Canada. 4(1): 33-47.

St. John, B.E., E.C. Carmack, R.J. Daley, C.B.J. Gray, and C.H. Pharo. 1976. The limnology of Kamloops Lake, British Columbia. Inland Water Dir. Rep. Environ. Canada. 167 p.

Shortreed, K.S., and J.G. Stockner. 1981. Limnological results from the 1979 British Columbia Lake Enrichment Program. Can. Tech. Rep. Fish. Aquat. Sci. 995: 71 p.

Stainton, M.P., M.J. Capel, and F.A.J. Armstrong. 1977. The Chemical Analysis of Fresh Water. 2nd edition. Can. Fish. and Mar. Serv. Misc. Spec. Publ. 25: 180 p.

Stephens, K., and R. Brandstaetter. 1983. A laboratory manual: collected methods for the analysis of water. Can. Tech. Rep. Fish. Aquat. Sci. 1159: 68 p.

Stockner, J.G. 1979. Lake fertilization as a means of enhancing sockeye salmon populations: the state of the art in the Pacific Northwest. Fish. Mar. Serv. Tech. Rep. 740: 14 p.

Stockner, J.G. 1981. Whole-lake fertilization for the enhancement of sockeye salmon (Oncorhynchus nerka) in British Columbia, Canada. Verh. Internat. Verein. Limnol. 21: 293-299.

Stockner, J.G., and K.S. Shortreed. 1975. Phytoplankton succession and primary production in Babine Lake, British Columbia. J. Fish. Res. Board Can. 32: 2413-2427.

Stockner, J.G., and K.S. Shortreed. 1978. Limnological survey of 35 sockeye salmon (Oncorhynchus nerka) nursery lakes in British Columbia and the Yukon Territory. Fish. Mar. Serv. Tech. Rep. 827: 47 p.

Stockner, J.G., and K.S. Shortreed. 1979. Limnological studies of 13 sockeye salmon (Oncorhynchus nerka) nursery lakes in British Columbia, Canada. Fish. Mar. Serv. Tech. Rep. 865: 125 p.

Stockner, J.G., K.S. Shortreed, and K. Stephens. 1980. The British Columbia lake fertilization program: limnological results from the first 2 years of nutrient enrichment. Can. Tech. Rep. Fish. Aquat. Sci. 924: 91 p.

Turner, J.S. 1973. Buoyancy effects of fluids. Cambridge Press, Cambridge. 367 p.

Utermöhl, H. 1958. Zur Vervollkommnung der Quantitativen Phytoplankton-Methodik. Mitt. Int. Ver. Limnol. 9: 1-38.

Vernon, E.H. MS 1982. Fraser River Sockeye: the stocks and their enhancement. Rep. prep. for DFO-Pacific. 53 p.

Vollenweider, R.A. 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication. OECD Rep. DAS/CSI/-68. 27: 159 p.

Ward, F.J. 1957. Seasonal and annual changes in availability of the adult crustacean plankters of Shuswap Lake. I.P.S.F.C. Prog. Rep. No. 3. 56 p.

Ward, F.J. 1964. Limnology of Kamloops Lake. I.P.S.F.C. Bull. 16.

Table 1. Salient physical and hydrologic information on the Fraser River study lakes.[a]

Lake	Latitude (°N)	Longitude (°W)	Elevation (m)	Drainage area (km^2)	Lake area (km^2)	Mean depth (m)	Water residence time (y)
Adams	51	119	407	3080	138	169	10.5
Anderson	50	122	258	730	28	140	7.1
Bowron	53	121	945	460	10	16	0.6
Chilko	51	124	1172	2110	200	108	16.4
Francois	54	125	715	3600	260	87	30.1
Fraser	54	124	670	6030	55	13	0.6
Harrison	49	121	10	8440	218	151	2.3
Lillooet	50	122	196	5180	35	62	0.6
Little Shuswap	50	119	347	16200	18	14	0.03
Mara	50	119	347	5430	19	18	0.1
Momich	51	119	472	480	2	32	0.2
Pitt	49	122	Tidal	880	54	46	1.4
Quesnel	52	121	725	5930	270	158	10.8
Seton	50	122	237	1040	24	85	0.6
Shuswap	50	119	347	16200	310	62	2.1
Stuart	54	124	678	14600	360	20	1.7
Takla	55	125	692	6370	260	107	15.4
Taseko	51	123	1321	1550	31	43	0.9
Trembleur	54	125	687	8750	117	40	1.9

[a]Unpublished data supplyed by the International Pacific Salmon Fisheries Commission.

Table 2. Salient limnological variables from Fraser River, B.C. coastal and Yukon River lakes.

Lake	Bacterial numbers ($x10^6 \cdot mL^{-1}$)	Chlorophyll ($\mu g \cdot L^{-1}$)	Zooplankton biomass (mg dry wt $\cdot m^{-2}$)
Fraser River System			
Zone A			
Francois	1.67	1.88	2552
Fraser	1.84	4.47	906
Stuart	1.61	2.03	702
Takla	1.26	1.68	601
Trembleur	1.31	1.72	1086
Zone A Mean	1.54	2.36	1169
Zone B			
Adams	0.95	1.70	771
Bowron	1.48	1.51	646
Little Shuswap	1.24	2.46	676
Mara	1.56	1.78	1151
Momich	1.10	2.13	412
Quesnel	0.91	1.23	622
Shuswap	1.68	1.63	1003
Zone B Mean	1.27	1.78	754
Zone C			
(Insular Mountain)			
Anderson	1.00	0.89	628
Chilko	0.66	0.93	164
Lillooet	1.12	0.83	156
Seton	1.24	1.40	312
Taseko	0.73	0.35	120
Mean	0.95	0.88	276
(Coastal Mountain)			
Harrison	1.22	0.78	200
Pitt	1.22	0.25	113
Zone C Mean[a]	1.00	0.86	263
Yukon River System			
Claire	1.74	1.47	2505
Fox	1.54	0.78	3122
Michie	3.53	1.92	2380
Sekulman	1.05	0.85	2045
Wellesley	2.28	1.65	5262
Mean	2.03	1.33	3063
British Columbia Coastal			
Kennedy-Main Arm	0.87	1.55	155
Simpson	1.60	1.48	125
Sproat	0.52	0.50	235
Woss	0.75	1.26	408
Yakoun	0.92	3.04	68
Mean	0.93	1.57	198

Table 2. Cont'd.

Lake	Total phosphorus ($\mu g \cdot L^{-1}$)	Total dissolved solids ($mg \cdot L^{-1}$)	Compensation depth (m)	Rank
Fraser River System				
Zone A				
Francois	4.5	76	9.7	4
Fraser	10.7	34	8.4	5
Stuart	3.5	78	7.9	3
Takla	3.5	48	7.8	1
Trembleur	3.5	58	7.6	2
Zone A Mean	5.1	59	8.3	
Zone B				
Adams	2.3	31	11.4	2
Bowron	3.8	49	10.4	3
Little Shuswap	3.5	52	8.2	7
Mara	5.0	69	13.1	6
Momich	3.5	32	6.9	5
Quesnel	2.0	62	20.5	1
Shuswap	3.7	53	12.5	4
Zone B Mean	3.4	50	11.9	
Zone C (Insular Mountain)				
Anderson	3.5	61	14.2	2
Chilko	2.9	39	20.9	1
Lillooet	21.1[a]	29	2.0	5
Seton	8.0[a]	45	4.9	6
Taseko	17.8[a]	29	1.8	7
Mean	3.2	41	8.8	
(Coastal Mountain)				
Harrison	3.3	40	9.8	4
Pitt	3.0	26	6.8	3
Zone C Mean[b]	3.2	40	8.9	
Yukon River System				
Claire	5.0	199	12.8	
Fox	6.0	222	8.7	
Michie	7.5	174	6.2	
Sekulman	6.5	59	7.5	
Wellesley	9.0	150	12.6	
Mean	6.8	161	9.6	
British Columbia Coastal				
Kennedy-Main Arm	1.3	26	5.6	
Simpson	1.5	16	7.7	
Sproat	1.2	37	28.3	
Woss	1.0	17	15.7	
Yakoun	1.0	29	14.3	
Mean	1.2	25	14.3	

[a] values excluded from mean total phosphorus value.
[b] excluding Pitt Lake values.

LIST OF APPENDIX TABLES

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Appendix Table 1. Salient physical data from the study lakes.

Lake and station	Surface temperature (°C)	Depth of maximum stability (m)	Schmidt stability function ($kg \cdot s^{-2}$)	Secchi depth (m)	Compensation depth (m)
Adams-1	13.3	17.3	1637	8.5	11.2
Adams-2	13.7	17.6	1528	8.0	11.4
Adams-3	13.1	23.2	1549	8.5	12.5
Anderson-1	11.9	28.0	587	11.0	16.0
Anderson-2	11.9	29.3	550	11.0	12.5
Bowron-1	8.9	U[a]	258	5.5	11.1
Bowron-2	9.4	24.5	162	5.0	9.6
Chilko-1	4.7	U	0	6.0	25.5
Chilko-2	4.9	U	3	5.0	28.2
Chilko-3	8.5	6.5	787	4.5	18.7
Chilko-4	8.5	21.8	176	3.0	11.5
Chilko-5	8.7	44.5	45	3.0	16.8
Chilko-6	10.5	34.2	204	7.0	24.8
Francois-1	11.5	20.2	1298	-	9.0
Francois-2	12.4	33.0	326	-	9.4
Francois-3	13.5	23.8	1039	-	10.7
Fraser-1	13.6	17.8	952	-	8.9
Fraser-2	13.7	U	53	4.0	7.8
Harrison-1	11.1	28.6	722	3.0	7.2
Harrison-2	11.9	39.0	168	3.5	10.0
Harrison-3	12.3	41.2	790	3.5	10.5
Harrison-4	12.8	40.5	510	5.0	10.6
Harrison-5	13.0	42.0	216	5.5	10.6
Lillooet-1	9.6	46.5	261	0.3	1.9
Lillooet-2	9.8	40.2	352	0.3	2.1
Little Shuswap-1	13.8	U	39	8.0	9.1
Little Shuswap-2	13.9	41.0	109	8.0	7.4
Mara-1	14.3	15.8	2163	7.0	16.3
Mara-2	14.2	14.2	1924	7.0	9.9
Momich-1	10.9	23.2	871	7.0	6.9
Pitt-1	5.0	U	0	3.0	6.6
Pitt-2	5.0	U	0	2.5	7.7
Pitt-3	5.4	U	0	2.2	6.0

Appendix Table 1. Cont'd.

Lake and station	Surface temperature (°C)	Depth of maximum stability (m)	Schmidt stability function ($kg \cdot s^{-2}$)	Secchi depth (m)	Compensation depth (m)
Quesnel-1	8.0	U	36	9.0	20.1
Quesnel-2	10.6	25.2	781	10.0	19.2
Quesnel-3	11.8	20.8	998	10.0	28.8
Quesnel-4	11.5	32.0	829	11.5	19.8
Quesnel-5	11.8	21.5	1037	11.0	18.8
Quesnel-6	12.0	19.8	910	11.0	19.6
Quesnel-7	12.5	19.9	1350	12.0	20.2
Quesnel-8	12.5	23.0	1199	13.0	17.2
Seton-1	11.0	31.6	375	1.5	4.5
Seton-2	11.2	31.5	554	2.5	5.3
Shuswap-1	14.2	12.8	2214	8.5	13.0
Shuswap-2	14.4	15.4	2427	10.0	12.9
Shuswap-3	14.5	10.8	3082	9.0	11.8
Shuswap-4	14.5	10.8	3113	8.5	12.8
Shuswap-5	14.1	16.0	2379	9.5	11.7
Shuswap-6	14.2	21.6	2193	11.0	12.8
Stuart-1	12.7	12.2	1575	7.0	8.1
Stuart-2	13.8	18.0	1686	7.5	8.3
Stuart-3	14.6	19.6	1744	7.0	7.3
Takla-1	12.5	16.2	1467	6.0	8.2
Takla-2	12.2	17.8	1398	5.5	7.7
Takla-3	11.7	13.2	1251	7.0	7.7
Takla-4	11.2	28.2	872	5.0	7.5
Taseko-1	8.2	43.0	67	0.3	1.8
Trembleur-1	12.8	16.3	1368	5.5	7.4
Trembleur-2	13.6	19.4	1747	7.0	7.7

Appendix Table 2. Total alkalinity, pH and dissolved inorganic carbon values for the study lakes.

Lake and station	Epilimnetic pH	Epilimnetic total alkalinity ($mg \cdot L^{-1} CaCO_3$)	Epilimnetic dissolved inorganic carbon ($mg\ C \cdot L^{-1}$)[a]
Adams-1	7.6	18.5	4.80
Adams-2	7.6	18.3	5.35
Adams-3	7.5	19.3	5.04
Anderson-1	8.0	32.0	7.88
Anderson-2	8.0	31.5	7.77
Bowron-1	7.3	32.8	9.07
Bowron-2	7.4	33.0	8.88
Chilko-1	7.4	18.3	4.99
Chilko-2	7.5	19.0	5.02
Chilko-3	7.8		
Chilko-4	7.6	19.0	4.86
Chilko-5	7.4	18.8	5.06
Chilko-6	8.0	19.3	4.78
Francois-1	7.4	32.8	8.69 (7.65)[b]
Francois-2	7.4	32.0	8.64 (7.42)
Francois-3	7.5	33.8	8.79 (7.56)
Fraser-1	7.6	41.8	10.77 (9.74)
Fraser-2	7.6	42.0	10.76 (9.94)
Harrison-1	7.3	13.0	3.61
Harrison-2	7.3	12.8	3.54
Harrison-3	7.3	12.8	3.48
Harrison-4	7.3	12.5	3.38
Harrison-5	7.4	13.0	3.52
Lillooet-1	7.4	14.5	3.92
Lillooet-2	7.4	14.3	3.98
Little Shuswap-1	7.6	29.3	7.48
Little Shuswap-2	7.7	30.5	7.76
Mara-1	7.6	41.5	10.56
Mara-2	7.5	40.5	10.51
Momich-1	7.2	13.0	3.67
Pitt-1	6.7	5.5	2.03 (1.55)
Pitt-2	6.8	5.2	1.79 (1.47)
Pitt-3	6.8	4.9	1.67 (1.44)

Appendix Table 2. Cont'd.

Lake and station	Epilimnetic pH	Epilimnetic total alkalinity ($mg \cdot L^{-1} CaCO_3$)	Epilimnetic dissolved inorganic carbon ($mg\ C \cdot L^{-1}$)[a]
Quesnel-1	7.8	44.8	11.22
Quesnel-2	7.8	43.8	10.92
Quesnel-3	7.9	44.5	11.04
Quesnel-4	7.6	44.8	11.41
Quesnel-5	7.6	43.8	11.22
Quesnel-6	7.9	44.5	11.01
Quesnel-7	7.8	43.5	10.96
Quesnel-8	7.7	43.3	10.88
Seton-1	7.6	28.0	7.16
Seton-2	7.6	28.0	7.18
Shuswap-1	7.6	38.5	9.92
Shuswap-2	7.6	35.3	9.10
Shuswap-3	7.5	32.8	8.53
Shuswap-4	7.2	33.0	9.12
Shuswap-5	7.4	29.5	7.76
Shuswap-6	7.6	30.8	7.88
Stuart-1	7.3	42.3	11.60 (9.78)
Stuart-2	7.2	41.0	11.31 (9.57)
Stuart-3	7.3	41.0	11.07 (8.71)
Takla-1	-	-	- (6.31)
Takla-2	7.6	27.5	7.01 (6.39)
Takla-3	7.4	29.3	7.93 (7.72)
Takla-4	7.2	29.3	8.18 (6.33)
Taseko-1	-	-	-
Trembleur-1	7.2	33.8	9.61 (7.90)
Trembleur-2	7.1	33.5	9.81 (8.16)

[a] [b] values determined using the potentiometric method (APHA 1976).
values in brackets determined using the gas chromatographic method (Stainton et al. 1977).

Appendix Table 3. Ammonia and nitrate concentrations in the study lakes.

Lake and station	Mean epilimnetic ammonia ($\mu g\ N \cdot L^{-1}$)	Hypolimnetic ammonia ($\mu g\ N \cdot L^{-1}$)	Mean epilimnetic nitrate ($\mu g\ N \cdot L^{-1}$)	Hypolimnetic nitrate ($\mu g\ N \cdot L^{-1}$)
Adams-1	6.5	11.0	30.5	118.5
Adams-2	8.0	<4.0	30.5	118.5
Adams-3	7.5	<4.0	42.5	116.5
Anderson-1	4.5	<4.0	2.0	48.0
Anderson-2	<4.0	<4.0	2.5	31.5
Bowron-1	7.0	-	63.0	-
Bowron-2	<4.0	<4.0	49.0	90.0
Chilko-1	4.5	-	25.2	-
Chilko-2	4.5	-	25.0	-
Chilko-3	<4.0	<4.0	8.5	19.0
Chilko-4	<4.0	4.5	7.5	16.5
Chilko-5	<4.0	-	9.0	-
Chilko-6	<4.0	-	3.5	-
Francois-1	<4.0	<4.0	21.5	46.5
Francois-2	<4.0	-	34.0	-
Francois-3	4.0	4.0	7.0	43.0
Fraser-1	<4.0	<4.0	15.7	15.0
Fraser-2	<4.0	-	7.2	-
Harrison-1	<4.0	4.0	46.0	71.0
Harrison-2	<4.0	<4.0	40.5	69.5
Harrison-3	<4.0	<4.0	38.5	77.5
Harrison-4	<4.0	<4.0	33.0	77.5
Harrison-5	7.5	-	45.2	-
Lillooet-1	<4.0	6.0	34.3	60.0
Lillooet-2	<4.0	4.0	26.5	77.0
Little Shuswap-1	<4.0	-	18.0	-
Little Shuswap-2	<4.0	-	20.2	-
Mara-1	<4.0	5.0	7.0	146.0
Mara-2	10.5	7.0	12.0	142.5
Momich-1	<4.0	<4.0	3.5	51.5
Pitt-1	4.2	-	107.5	-
Pitt-2	<4.0	-	112.5	-
Pitt-3	7.5	-	113.5	-

Appendix Table 3. Cont'd.

Lake and station	Mean epilimnetic ammonia ($\mu g\ N \cdot L^{-1}$)	Hypolimnetic ammonia ($\mu g\ N \cdot L^{-1}$)	Mean epilimnetic nitrate ($\mu g\ N \cdot L^{-1}$)	Hypolimnetic nitrate ($\mu g\ N \cdot L^{-1}$)
Quesnel-1	<4.0	-	128.8	-
Quesnel-2	<4.0	<4.0	88.0	135.0
Quesnel-3	6.5	<4.0	67.5	137.5
Quesnel-4	7.5	7.5	80.0	129.0
Quesnel-5	4.5	<4.0	78.0	140.0
Quesnel-6	5.5	7.5	73.0	135.0
Quesnel-7	8.5	<4.0	66.5	132.5
Quesnel-8	8.0	<4.0	61.0	135.0
Seton-1	<4.0	<4.0	11.0	27.0
Seton-2	4.0	<4.0	13.0	40.5
Shuswap-1	<4.0	<4.0	9.5	108.0
Shuswap-2	<4.0	<4.0	6.0	111.0
Shuswap-3	4.5	<4.0	6.0	114.0
Shuswap-4	7.5	7.5	7.0	107.5
Shuswap-5	<4.0	<4.0	10.5	112.5
Shuswap-6	<4.0	<4.0	10.0	109.0
Stuart-1	4.5	<4.0	14.0	79.5
Stuart-2	<4.0	<4.0	8.0	91.0
Stuart-3	5.0	<4.0	5.5	56.5
Takla-1	5.0	<4.0	40.0	86.5
Takla-2	4.0	<4.0	45.0	91.0
Takla-3	8.5	<4.0	52.0	99.5
Takla-4	<4.0	<4.0	53.0	85.0
Taseko-1	4.2	-	24.0	-
Trembleur-1	6.0	<4.0	44.0	79.0
Trembleur-2	5.5	<4.0	31.0	88.0

[a] a "less than" sign indicates that all samples in the epilimnion are below detection limits.

Appendix Table 4. Phosphorus concentrations in the study lakes.

Lake and station	Mean epilimnetic total phosphorus ($\mu g\ P \cdot L^{-1}$)	Hypolimnetic total phosphorus ($\mu g\ P \cdot L^{-1}$)	Mean epilimnetic total dissolved phosphorus ($\mu g\ P \cdot L^{-1}$)	Hypolimnetic total dissolved phosphorus ($\mu g\ P \cdot L^{-1}$)
Adams-1	1.5	2.0	<1.0	2.0
Adams-2	3.0	1.5	2.0	1.0
Adams-3	2.5	2.5	1.5	2.0
Anderson-1	4.0	4.0	1.0	1.0
Anderson-2	3.0	2.0	1.0	1.0
Bowron-1	4.0	-	1.8	-
Bowron-2	3.7	4.0	3.3	2.0
Chilko-1	3.8	-	2.5	-
Chilko-2	2.5	-	1.8	-
Chilko-3	3.0	2.5	1.0	<1.0
Chilko-4	3.0	4.0	1.5	<1.0
Chilko-5	3.0	-	1.0	-
Chilko-6	2.2	-	1.0	-
Francois-1	5.0	4.0	2.5	3.0
Francois-2	3.5	-	3.0	-
Francois-3	5.0	3.5	2.5	2.5
Fraser-1	10.7	7.0	7.3	8.0
Fraser-2	10.7	-	8.2	-
Harrison-1	3.5	2.5	1.5	1.5
Harrison-2	3.5	4.0	1.5	1.5
Harrison-3	3.0	2.5	2.0	1.5
Harrison-4	3.5	2.0	2.0	1.0
Harrison-5	2.8	-	1.2	-
Lillooet-1	22.7	26.0	4.7	5.0
Lillooet-2	19.5	39.0	4.0	5.0
Little Shuswap-1	3.8	-	1.8	-
Little Shuswap-2	3.2	-	2.2	-
Mara-1	4.5	5.5	3.5	3.0
Mara-2	5.5	3.5	1.0	2.0
Momich-1	3.5	2.5	3.0	2.5
Pitt-1	3.2	-	-	-
Pitt-2	3.0	-	-	-
Pitt-3	2.8	-	-	-

Appendix Table 4. Cont'd.

Lake and station	Mean epilimnetic total phosphorus ($\mu g\ P \cdot L^{-1}$)	Hypolimnetic total phosphorus ($\mu g\ P \cdot L^{-1}$)	Mean epilimnetic total dissolved phosphorus ($\mu g\ P \cdot L^{-1}$)	Hypolimnetic total dissolved phosphorus ($\mu g\ P \cdot L^{-1}$)
Quesnel-1	1.8	-	<1.0	-
Quesnel-2	1.5	2.5	1.5	2.0
Quesnel-3	1.0	2.0	1.0	<1.0
Quesnel-4	2.5	1.5	<1.0	1.0
Quesnel-5	1.5	1.5	1.5	<1.0
Quesnel-6	1.5	2.5	1.0	1.0
Quesnel-7	2.5	1.5	<1.0	2.0
Quesnel-8	3.5	2.0	1.0	1.0
Seton-1	8.0	7.5	3.0	3.5
Seton-2	8.0	6.0	3.0	3.0
Shuswap-1	6.0	5.0	1.5	1.0
Shuswap-2	4.5	2.5	3.0	1.5
Shuswap-3	3.0	3.0	1.5	1.5
Shuswap-4	2.0	1.0	1.0	1.5
Shuswap-5	4.0	1.0	1.0	1.0
Shuswap-6	3.0	2.0	1.5	1.0
Stuart-1	4.5	2.0	2.0	2.5
Stuart-2	3.0	3.5	2.0	2.0
Stuart-3	3.0	1.5	1.0	1.5
Takla-1	2.0	3.0	2.0	2.5
Takla-2	2.0	2.5	3.5	2.5
Takla-3	3.0	3.0	3.0	2.0
Takla-4	3.5	3.5	3.0	1.5
Taseko-1	17.8	-	5.2	-
Trembleur-1	3.0	3.0	2.5	2.0
Trembleur-2	4.0	2.5	2.0	2.0

[a] a "less than" sign indicates that all samples in the epilimnion are below detection limits.

Appendix Table 5. Silicon, total dissolved solids and bacteria numbers in the study lakes.

Lake and station	Mean epilimnetic soluble reactive silicon (mg $Si \cdot L^{-1}$)	Hypolimnetic soluble reactive silicon (mg $Si \cdot L^{-1}$)	Epilimnetic total dissolved solids ($mg \cdot L^{-1}$)	Mean epilimnetic bacteria numbers ($x10^6 \cdot mL^{-1}$)
Adams-1	2.48	2.72	30.8	1.06
Adams-2	2.49	2.68	25.5	0.94
Adams-3	2.54	2.72	36.1	0.85
Anderson-1	1.82	2.05	60.0	1.22
Anderson-2	1.84	2.00	61.7	0.79
Bowron-1	1.54	-	51.3	1.42
Bowron-2	1.45	1.60	46.0	1.54
Chilko-1	1.05	-	37.3	0.46
Chilko-2	1.05	-	40.2	0.44
Chilko-3	1.04	1.05	36.5	0.75
Chilko-4	1.04	1.04	37.2	0.75
Chilko-5	1.06	-	40.5	0.69
Chilko-6	1.04	-	40.4	0.85
Francois-1	0.87	1.04	59.5	1.57
Francois-2	0.97	-	92.7	1.55
Francois-3	0.90	1.02		1.89
Fraser-1	1.74	1.76	32.4	1.87
Fraser-2	1.72	-	34.5	1.81
Harrison-1	2.06	2.16	38.8	1.12
Harrison-2	2.02	2.16	37.6	1.28
Harrison-3	2.01	2.20	42.8	1.30
Harrison-4	2.02	2.18	40.0	1.31
Harrison-5	2.06	-	39.4	1.07
Lillooet-1	2.24	2.70	28.8	1.10
Lillooet-2	2.04	3.09	29.2	1.13
Little Shuswap-1	2.39	-	48.7	1.04
Little Shuswap-2	2.40	-	56.4	1.43
Mara-1	2.85	3.30	70.5	1.69
Mara-2	2.81	3.26	66.7	1.42
Momich-1	3.13	3.48	31.9	1.10
Pitt-1	1.53	-	26.0	1.32
Pitt-2	1.41	-	26.4	1.39
Pitt-3	1.40	-	26.3	0.95

Appendix Table 5. Cont'd.

Lake and station	Mean epilimnetic soluble reactive silicon (mg $Si \cdot L^{-1}$)	Hypolimnetic soluble reactive silicon (mg $Si \cdot L^{-1}$)	Epilimnetic total dissolved solids ($mg \cdot L^{-1}$)	Mean epilimnetic bacteria numbers ($\times 10^6 \cdot mL^{-1}$)
Quesnel-1	1.46	-	59.0	0.69
Quesnel-2	1.42	1.56	57.2	1.01
Quesnel-3	1.39	1.58	56.0	0.96
Quesnel-4	1.31	1.51	53.7	1.04
Quesnel-5	1.41	1.60	66.0	0.74
Quesnel-6	1.42	1.66	78.4	0.89
Quesnel-7	1.43	1.63	62.5	1.00
Quesnel-8	1.48	1.68	61.3	0.96
Seton-1	2.14	2.18	43.6	1.40
Seton-2	2.14	2.23	45.7	1.08
Shuswap-1	2.64	2.82	67.5	1.94
Shuswap-2	2.52	2.48	54.7	1.78
Shuswap-3	2.52	2.42	56.4	1.77
Shuswap-4	2.34	2.42	41.8	1.38
Shuswap-5	2.24	2.55	47.2	1.50
Shuswap-6	2.28	2.57	50.4	1.73
Stuart-1	1.98	2.27	71.2	1.90
Stuart-2	2.09	2.54	70.7	1.52
Stuart-3	1.96	2.25	90.0	1.40
Takla-1	2.16	2.25	48.1	1.23
Takla-2	2.14	2.26	48.4	1.37
Takla-3	2.22	2.31	48.9	1.13
Takla-4	2.22	2.28	47.7	1.30
Taseko-1	1.55	-	29.1	0.73
Trembleur-1	2.29	2.40	58.7	1.35
Trembleur-2	2.20	2.38	57.3	1.27

Appendix Table 6. Mean epilimnetic phytoplankton biomass and areal zooplankton biomass in the study lakes.

Lake and station	Mean epilimnetic chlorophyll ($\mu g \cdot L^{-1}$)	Mean epilimnetic total algal volume ($mm^3 \cdot m^{-3}$)	Mean epilimnetic nano-plankton volume ($mm^3 \cdot m^{-3}$)[a]	Areal zooplankton biomass (mg dry weight $\cdot m^{-2}$)
Adams-1	1.39	80	54	588
Adams-2	1.69	64	47	732
Adams-3	2.02	59	41	992
Anderson-1	0.91	324	93	668
Anderson-2	0.88	366	47	588
Bowron-1	1.25	107	33	532
Bowron-2	1.77	136	48	760
Chilko-1	0.13	42	9	138
Chilko-2	0.14	35	7	125
Chilko-3	1.13	37	28	175
Chilko-4	1.51	71	59	275
Chilko-5	1.35	78	65	105
Chilko-6	1.34	73	45	165
Francois-1	2.19	198	65	-
Francois-2	1.87	251	64	2552
Francois-3	1.58	148	51	-
Fraser-1	3.60	279	51	582
Fraser-2	5.34	377	78	1229
Harrison-1	0.65	68	23	168
Harrison-2	0.77	73	31	290
Harrison-3	0.72	81	38	185
Harrison-4	0.92	85	48	235
Harrison-5	0.85	81	51	125
Lillooet-1	0.93	26	13	230
Lillooet-2	0.73	78	25	82
Little Shuswap-1	2.41	173	57	318
Little Shuswap-2	2.51	146	48	1035
Mara-1	1.82	121	53	1562
Mara-2	1.75	100	51	740
Momich-1	2.13	65	33	412
Pitt-1	0.17	5	4	125
Pitt-2	0.28	20	7	105
Pitt-3	0.31	13	10	110

Appendix Table 6. Cont'd.

Lake and station	Mean epilimnetic chlorophyll ($\mu g \cdot L^{-1}$)	Mean epilimnetic total algal volume ($mm^3 \cdot m^{-3}$)	Mean epilimnetic nano-plankton volume ($mm^3 \cdot m^{-3}$)[a]	Areal zooplankton biomass (mg dry weight $\cdot m^{-2}$)
Quesnel-1	1.06	53	21	422
Quesnel-2	1.21	75	31	512
Quesnel-3	1.41	62	27	640
Quesnel-4	1.27	92	41	550
Quesnel-5	1.32	85	36	760
Quesnel-6	1.49	72	31	485
Quesnel-7	1.19	61	26	915
Quesnel-8	0.91	97	42	695
Seton-1	1.63	148	57	310
Seton-2	1.18	292	44	315
Shuswap-1	2.27	151	73	1158
Shuswap-2	1.68	297	67	1178
Shuswap-3	1.34	90	57	905
Shuswap-4	1.18	63	42	642
Shuswap-5	1.31	115	53	950
Shuswap-6	1.98	93	59	1185
Stuart-1	2.13	300	71	675
Stuart-2	2.15	298	56	1272
Stuart-3	1.81	427	57	158
Takla-1	1.36	79	27	195
Takla-2	1.44	94	29	728
Takla-3	1.78	88	29	1292
Takla-4	2.13	257	47	190
Taseko-1	0.35	3	2	120
Trembleur-1	1.63	140	52	660
Trembleur-2	1.81	191	40	1512

[a] nanoplankton is that portion of the phytoplankton which has a maximum dimension of less than 20 μm.

Fig. 1. Map of British Columbia showing locations of study lakes.

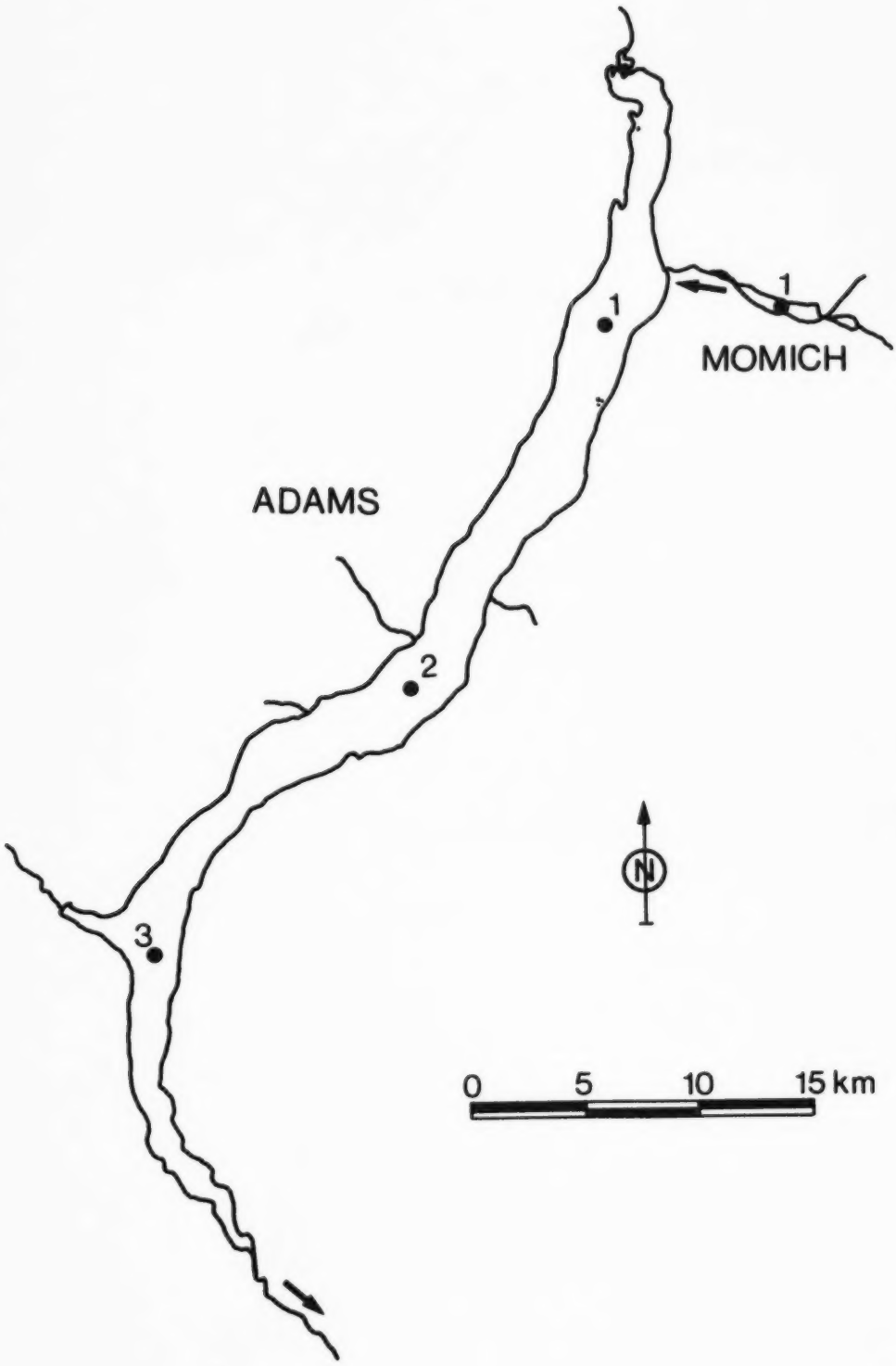

Fig. 2. Map showing station locations at Adams and Momich lakes.

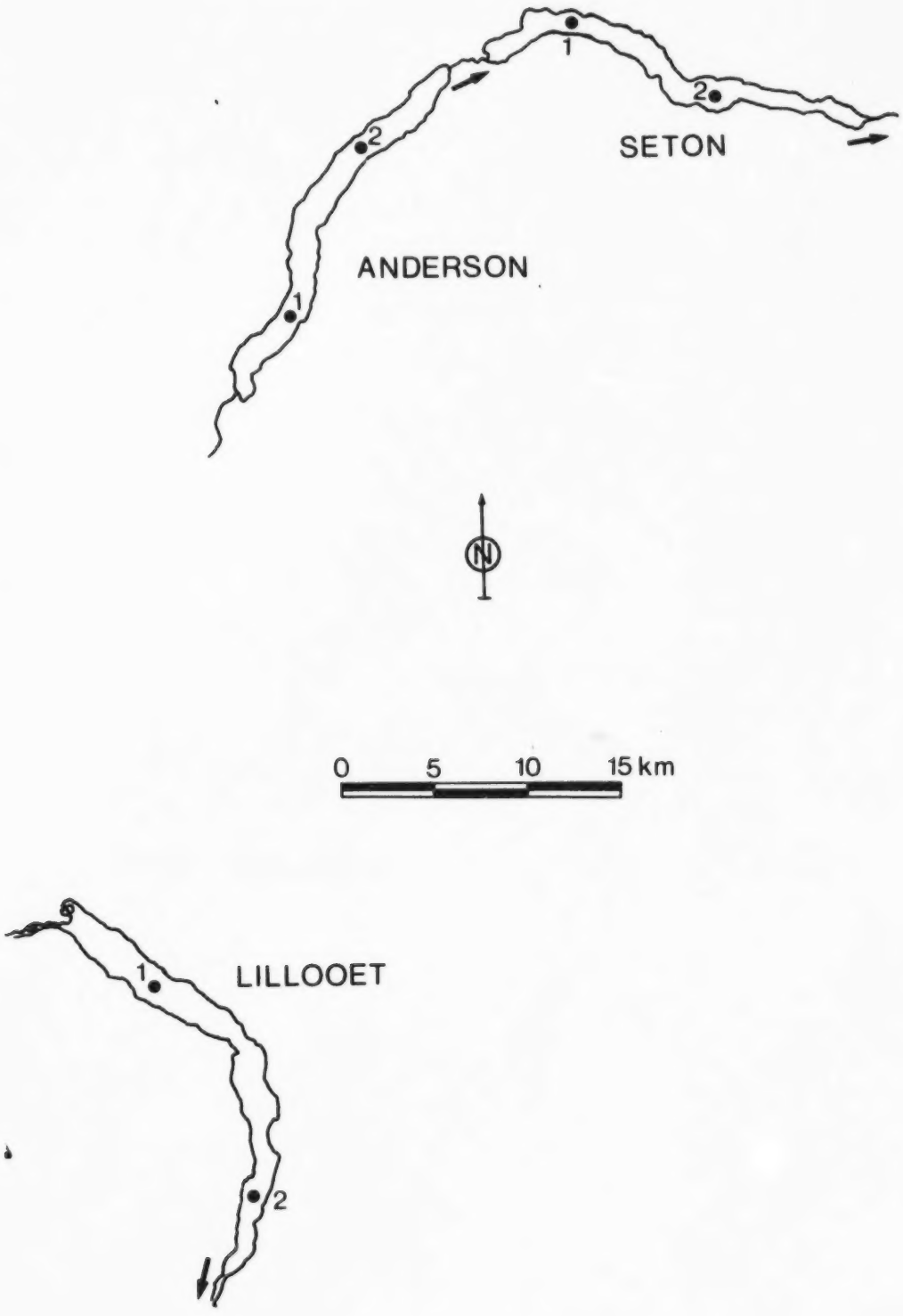

Fig. 3. Map showing station locations at Anderson, Seton and Lillooet lakes.

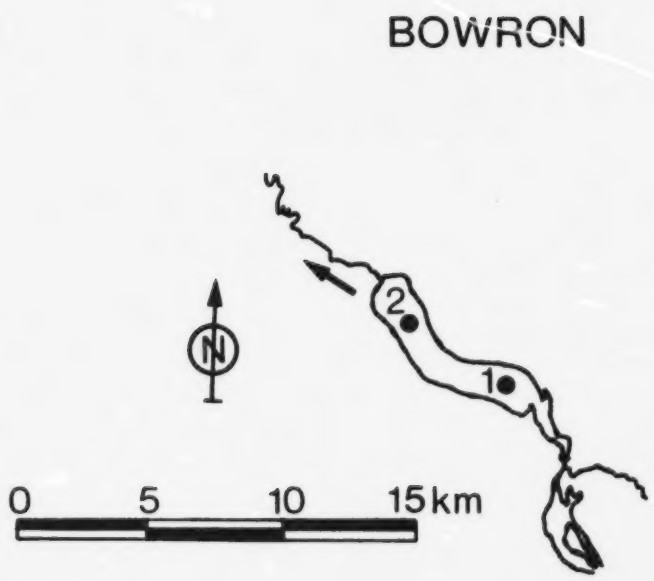

Fig. 4. Map showing station locations at Bowron Lake.

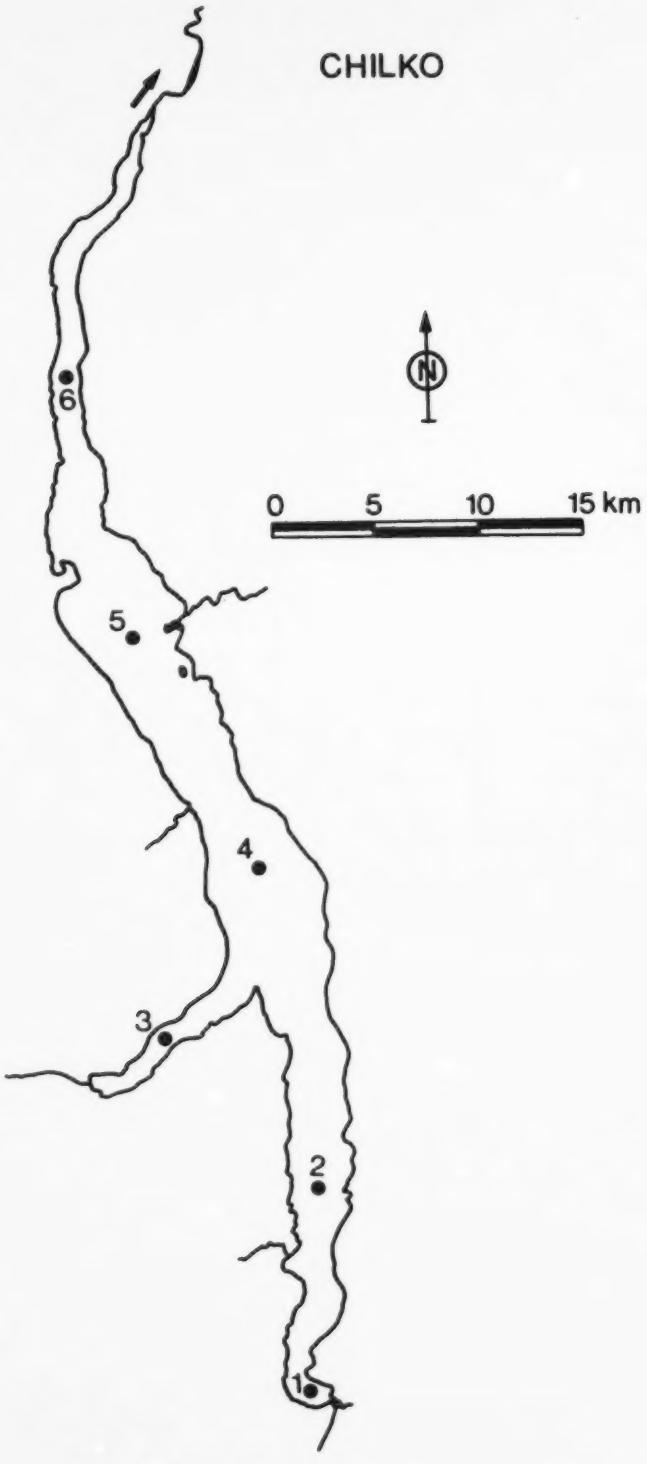

Fig. 5. Map showing station locations at Chilko Lake.

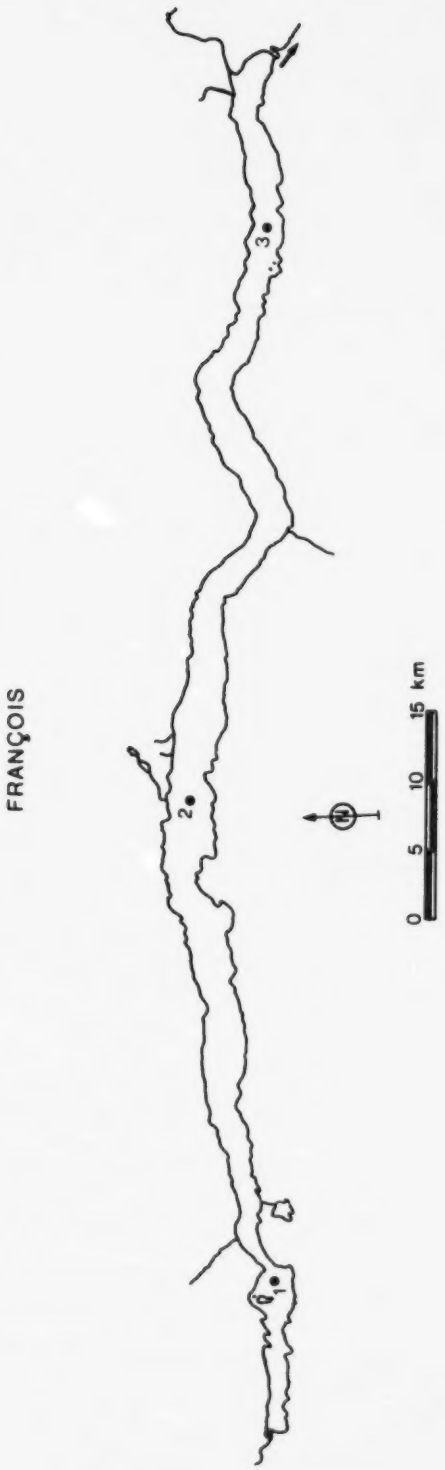

Fig. 6. Map showing station locations at Francois Lake.

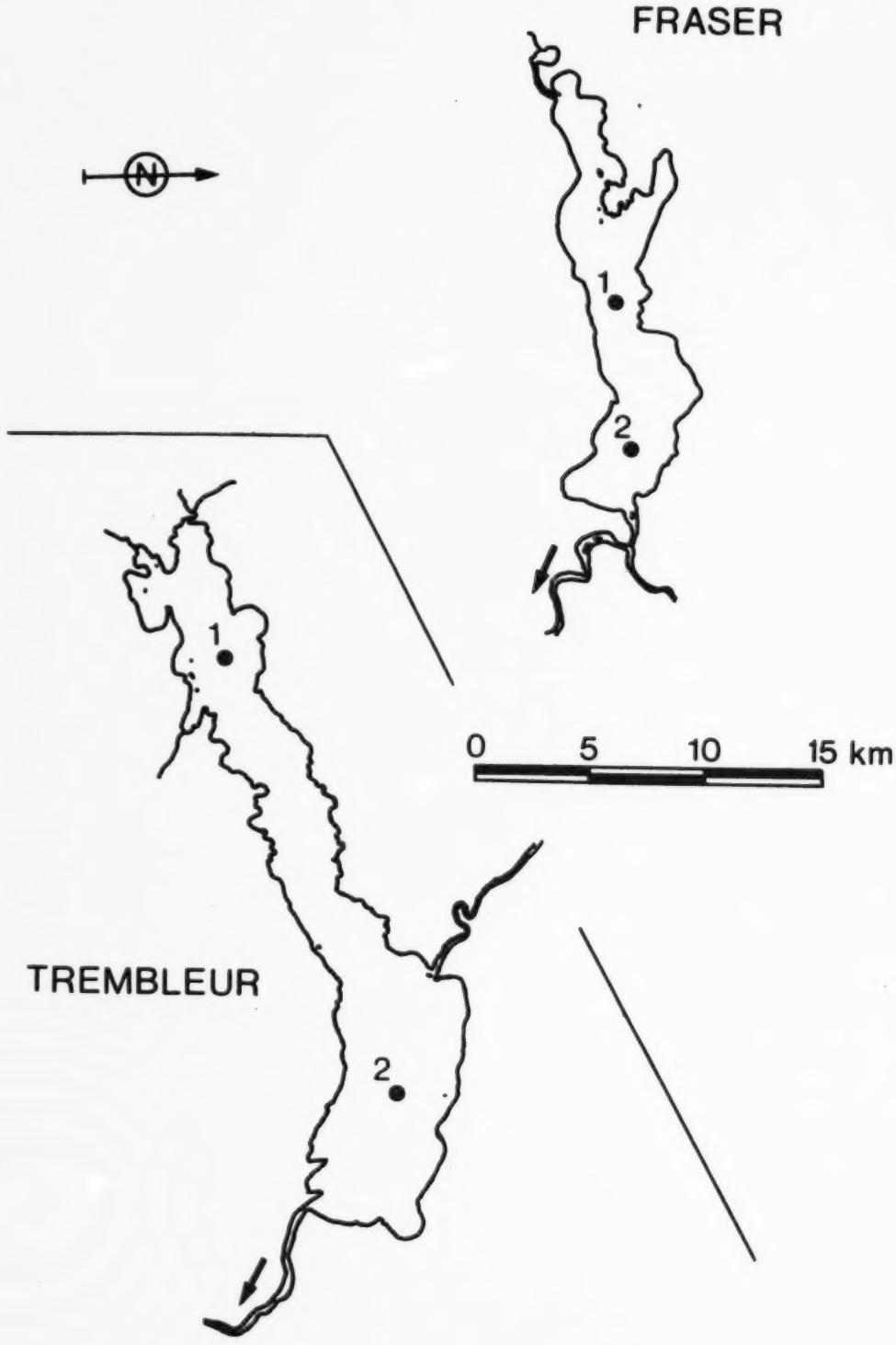

Fig. 7. Map showing station locations at Fraser and Trembleur lakes.

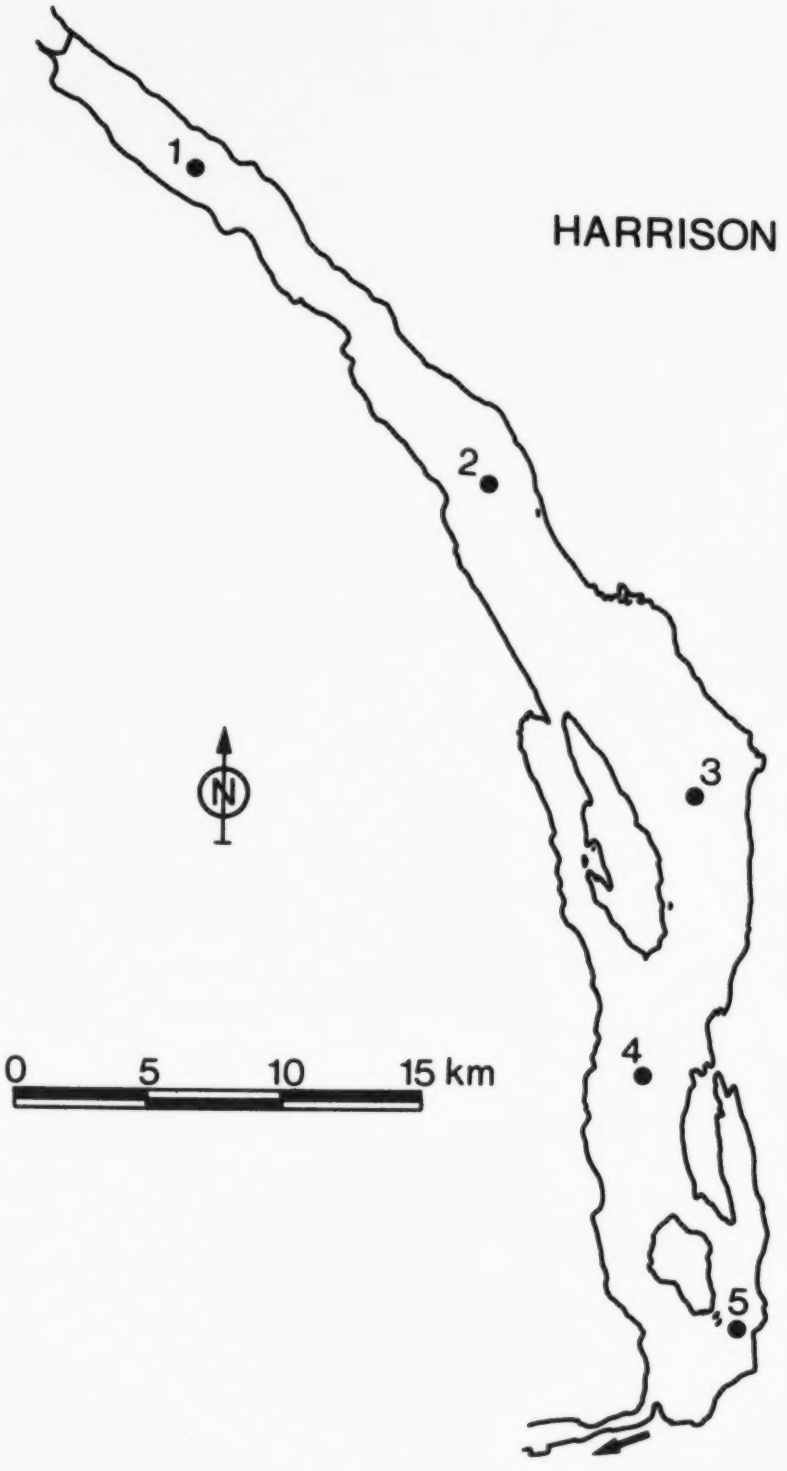

Fig. 8. Map showing station locations at Harrison Lake.

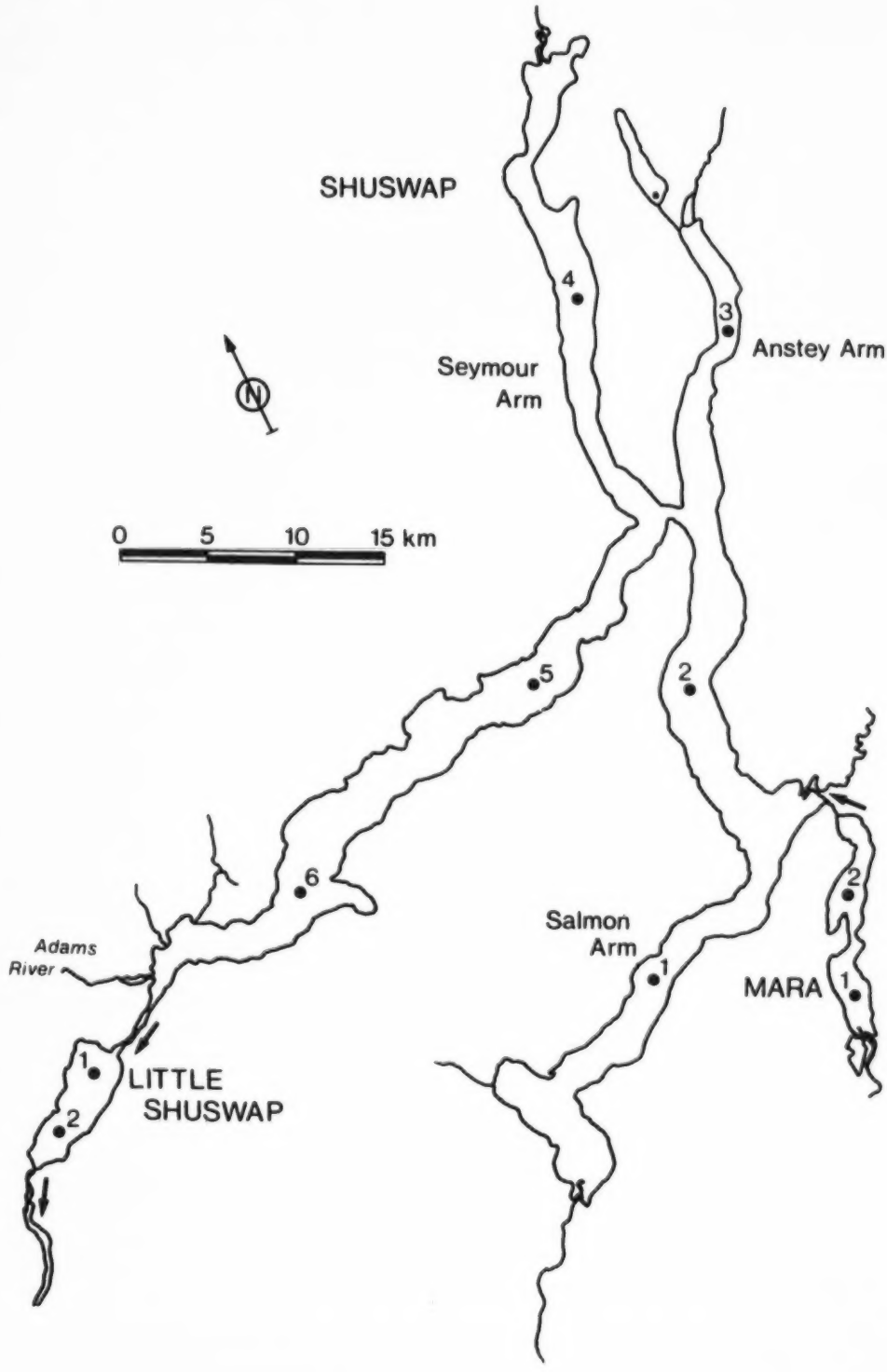

Fig. 9. Map showing station locations at Little Shuswap, Shuswap and Mara lakes.

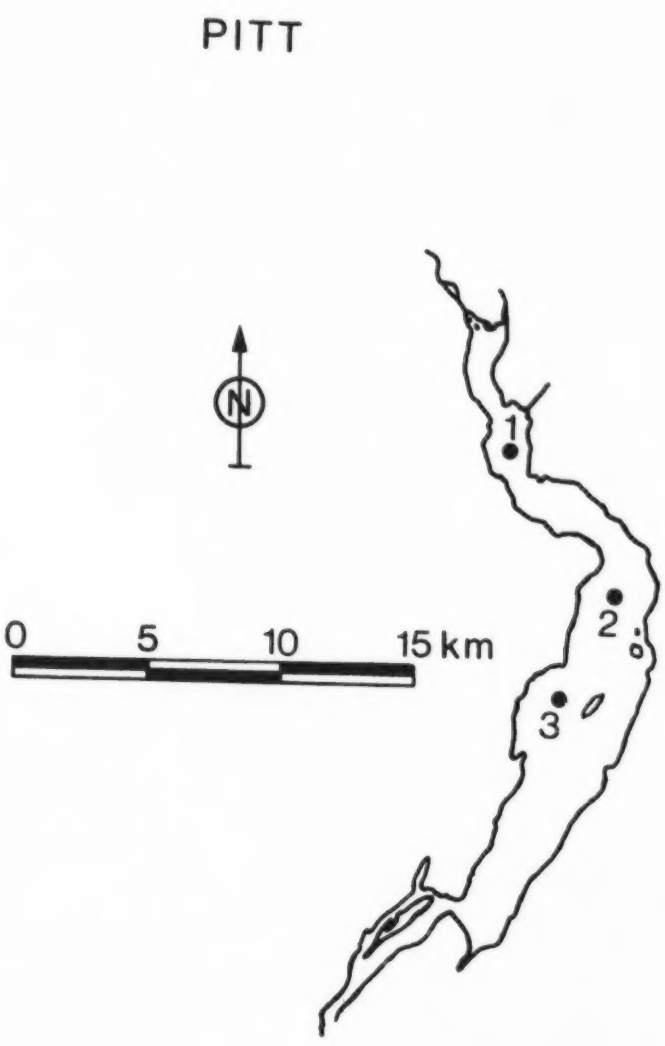

Fig. 10. Map showing station locations at Pitt Lake.

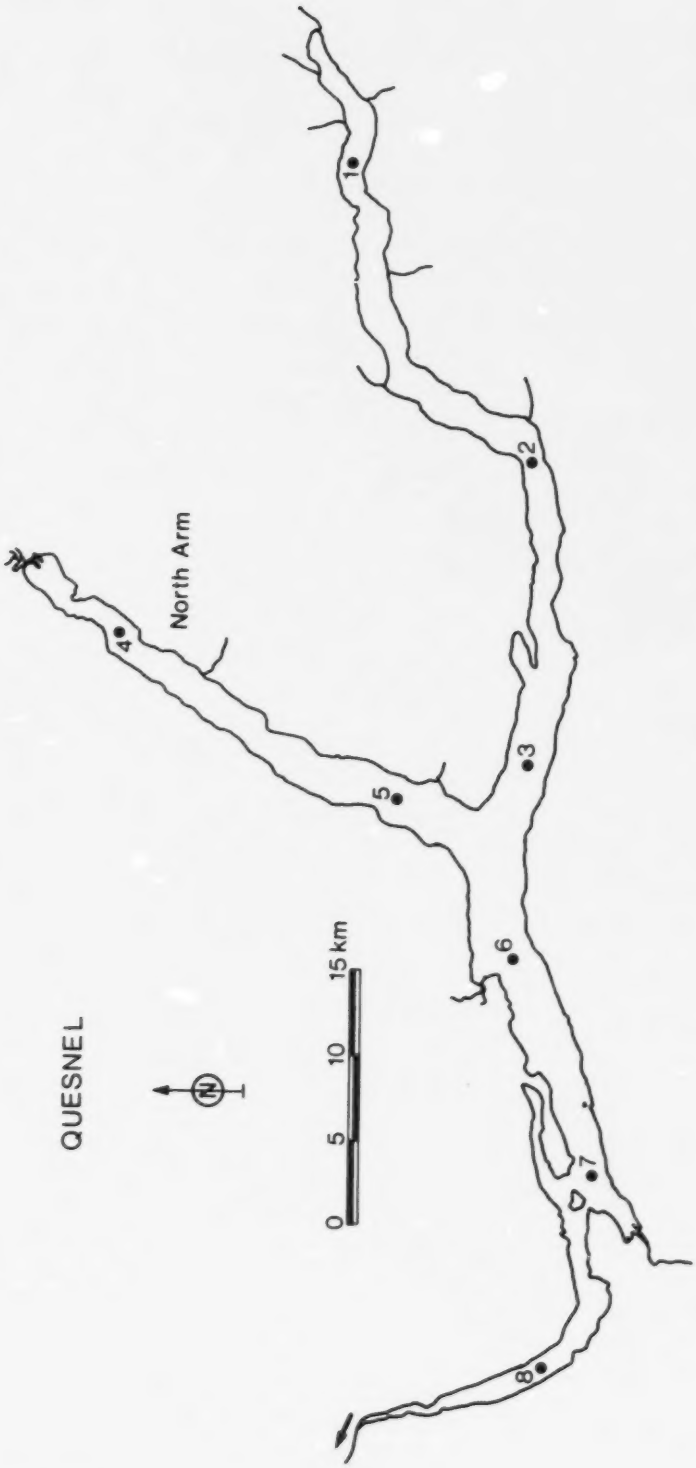

Fig. 11. Map showing station locations at Quesnel Lake.

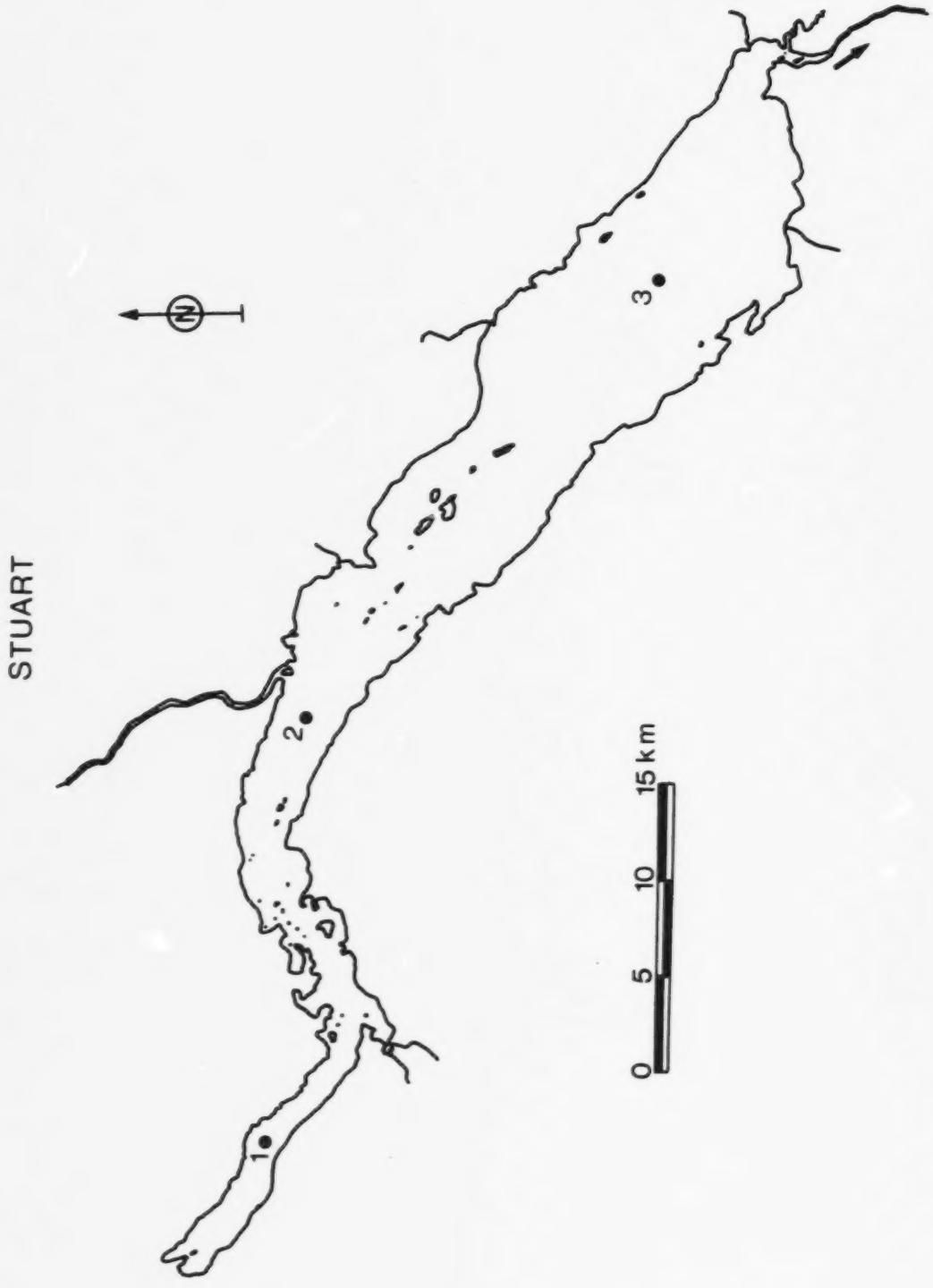

Fig. 12. Map showing station locations at Stuart Lake.

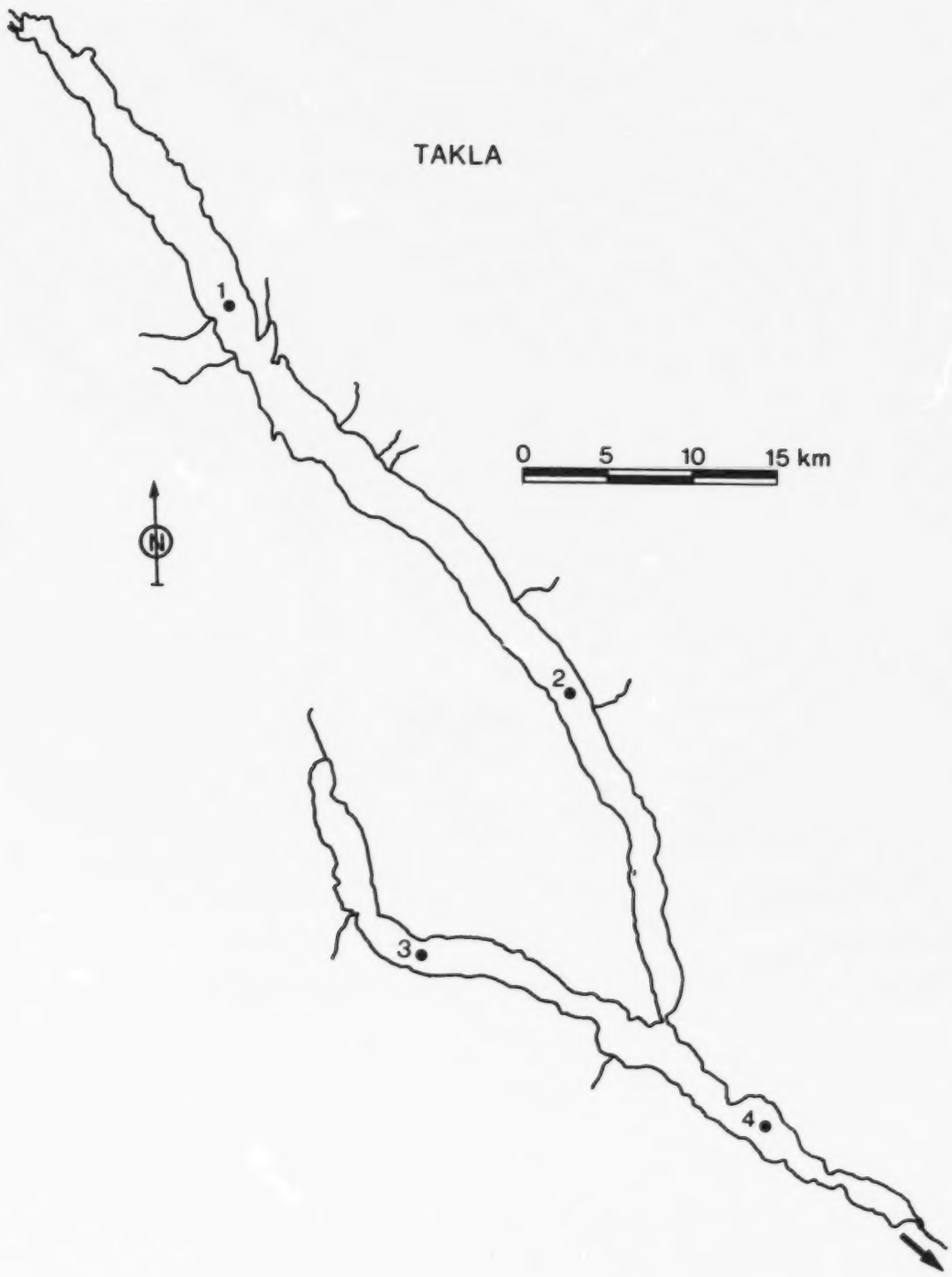

Fig. 13. Map showing station locations at Takla Lake.

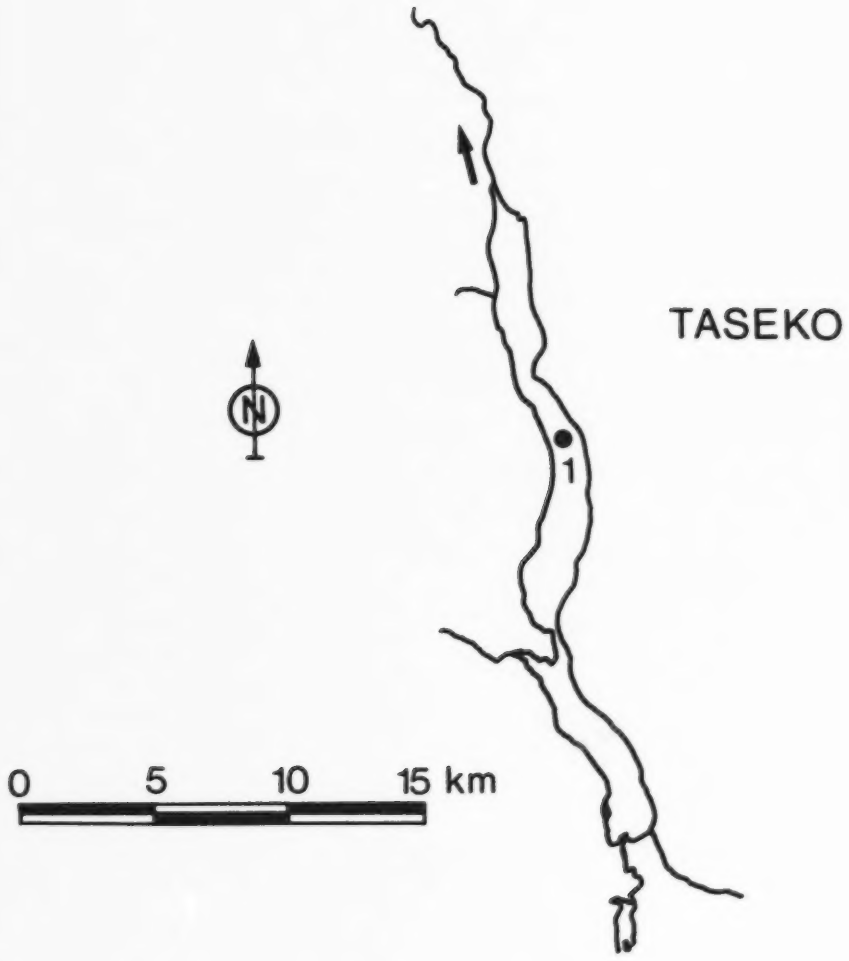

Fig. 14. Map showing station location at Taseko Lake.

Legend for Figures 15 and 16.

Histograms of chlorophyll and zooplankton biomass from Fraser and British Columbia coastal lakes.

LAKE	CODE
Fraser Lakes	
Zone A	
Takla	1
Trembleur	2
Stuart	3
Francois	4
Fraser	5
Zone B	
Bowron	6
Quesnel	7
Adams	8
Momich	9
Shuswap	10
Mara	11
Little Shuswap	12
Zone C	
Chilko	13
Taseko	14
Seton	15
Anderson	16
Lillooet	17
Harrison	18
Pitt	19
British Columbia Coastal	
Untreated	
Simpson	20
Sproat	21
Woss	22
Treated	
Hobiton	23
Bonilla	24
Great Central	25

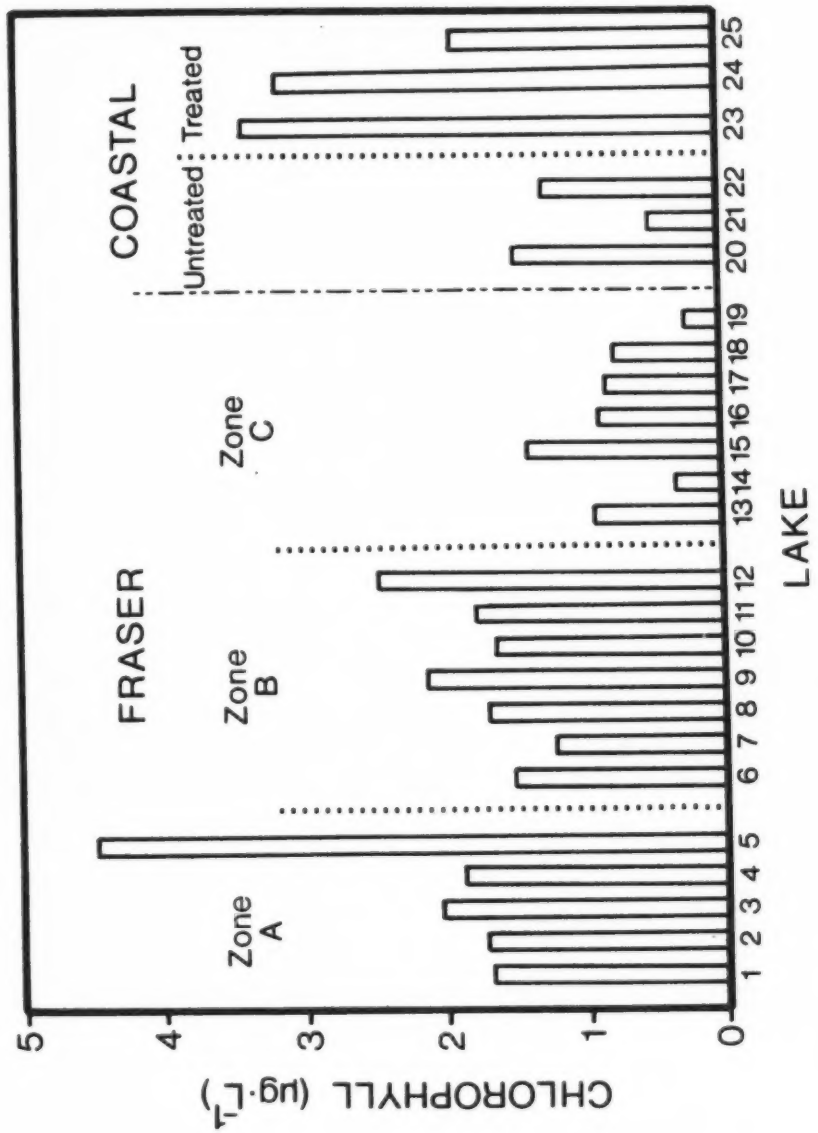

Fig. 15. Chlorophyll values for Fraser and B.C. coastal lakes.

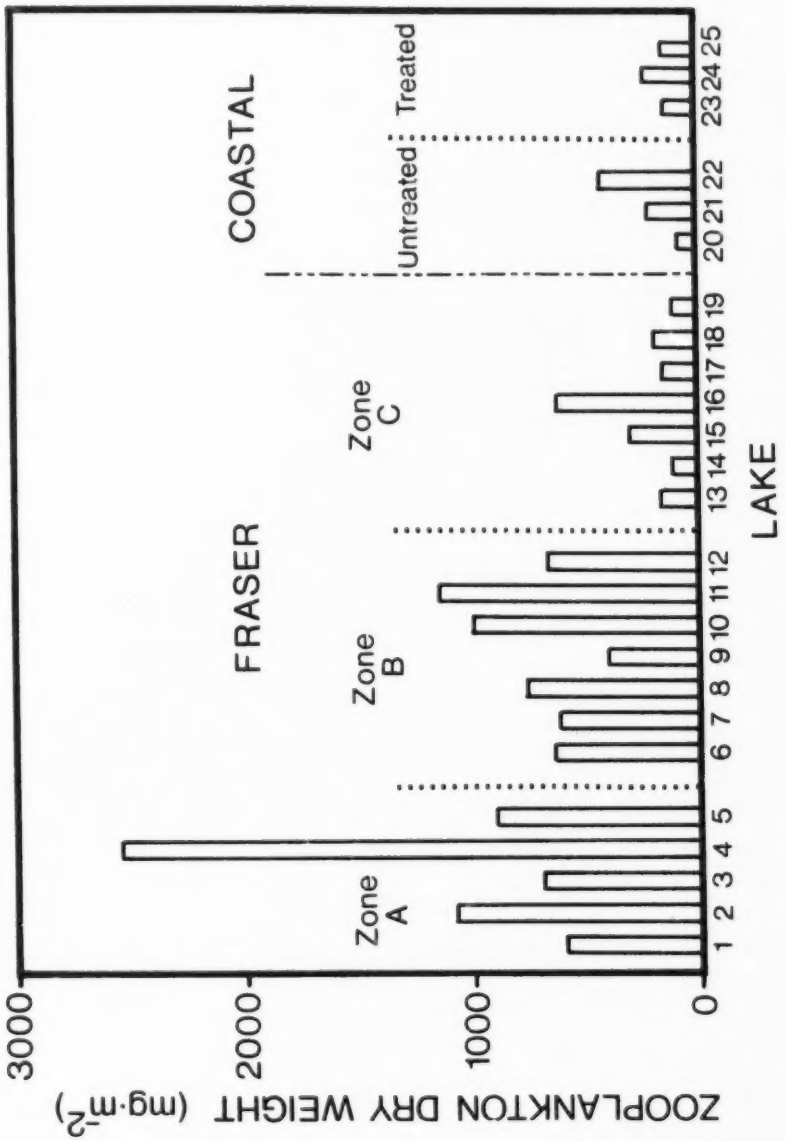

Fig. 16. Zooplankton biomass values for Fraser and B.C. coastal lakes.

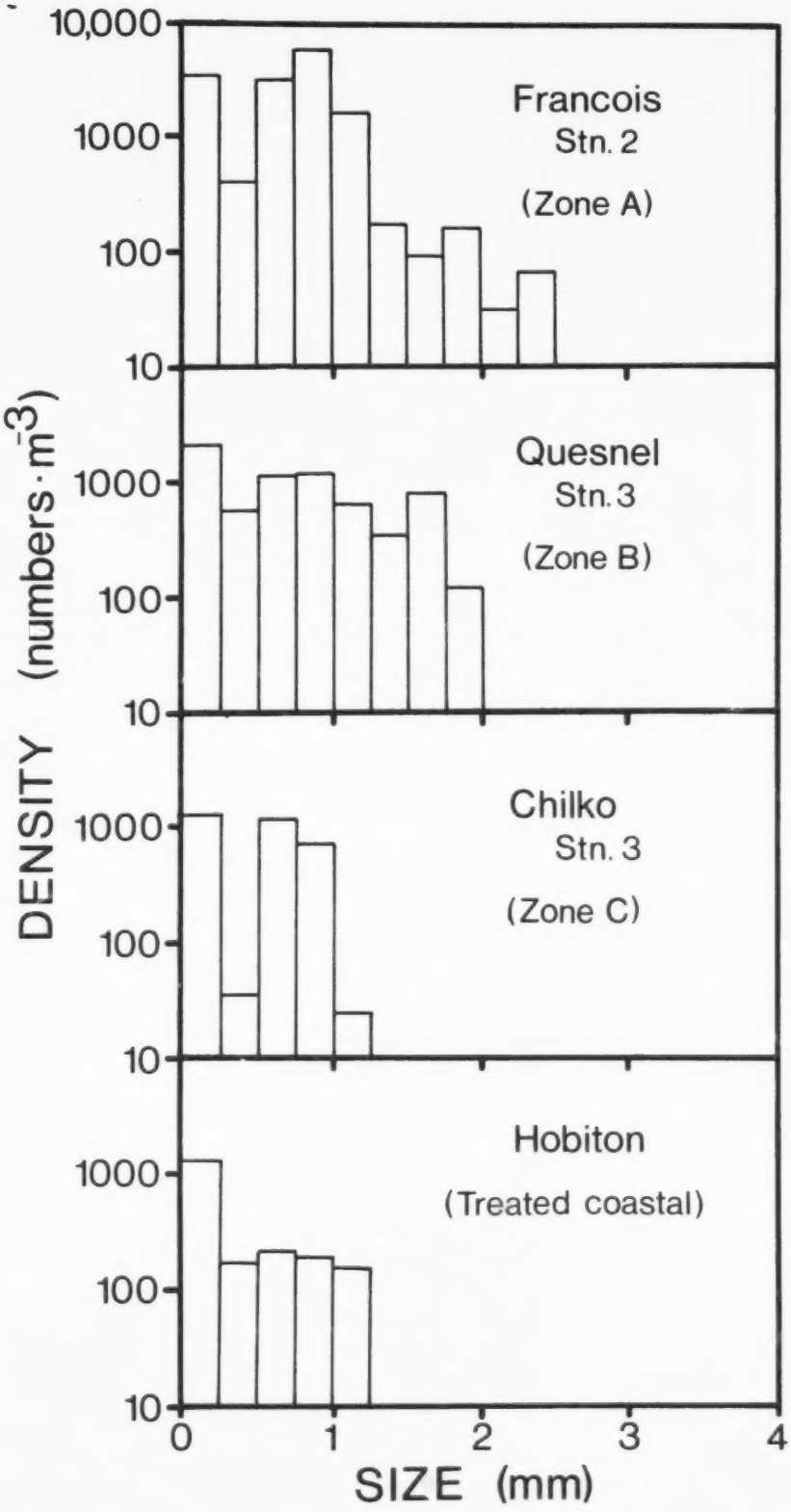

Fig. 17. Zooplankton size-frequency histograms from selected lakes (P. Rankin, unpubl. data).